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DC FURNACE TECHNOLOGY IN THE METALLURGICAL INDUSTRY

Report No 88-81-K

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ABSTRACT

Ontario Hydro Research Division was contracted by Marketing Operations Division to carry out a state-of-the-art study on DC arc furnace technology.

Two consultants were employed to cover the ferrous and the non-ferrous industry. The study is based on a review of the literature, information gained through visits made to DC furnace operations, and on discussions with furnace suppliers and others knowledgeable in the field of electric furnace technology. The main indicated advantages of the DC over the AC arc furnace in the steel industry are reduced electrode and refractory consumption as well as lower disturbance on the power grid. To date no advantages of DC over AC operation have been demonstrated in the non-ferrous industry, primarily since this industry has done little investigative work on DC technology.

The metallurgical industry in Ontario is receptive to the adoption of DC technology if economic benefits can be demonstrated.

At present, three commercial DC steel making arc furnaces are operating in the Western world, two in the U.S. and one in France. The only non-ferrous commercial DC operation is located in South Africa producing high carbon ferrochrome.

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80-110-111 11-216-112	808.275 817.32	May 12, 1988	88-81-K

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EXECUTIVE SUMMARY

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This state-of-the-art study on DC arc furnace technology combines a review of the literature with the knowledge gained from visits to DC furnace operations and contacts with furnace suppliers. It further contains current Ontario electric arc furnace plant descriptions and general industrial opinions as to the applicability of DC technology in today's metallurgical plants.

Background

Major developments in the steel industry have greatly improved AC electric furnace technology since the early 1960's. The introduction of Ultra High Power (UHP) AC electric arc furnaces, oxy-fuel burners, foamy slags, computer control, water cooled side walls and roofs, and ladle technology has resulted in very efficient operations. However, these highly efficient AC units still suffer from shortcomings such as high noise levels, disturbances to the supply system of the utilities, and high graphite electrode consumption costs. The development of power semiconductors, specifically thyristors of high current carrying capacity has opened the way for electric arc furnace suppliers to consider the use of DC current. For these reasons, considerable effort has been placed on the development of DC arc furnaces for the steel industry which, at least, on a theoretical basis are capable of overcoming the shortcomings of the AC arc furnace.

The incentive for the non-ferrous industry to adopt DC arc furnace technology is not as well defined. The potential advantages which have been suggested for DC over AC are higher furnace productivity resulting from higher limiting power densities, and also improved melt-in characteristics of fines fed through hollow electrodes. The efficiency of slag cleaning furnaces also may be improved. This all has to be demonstrated on a pilot plant scale before industry will consider adoption of DC furnace technology.

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Current Status

Commencing with the development work carried out by ASEA in 1972 at MEFOS (Sweden) the development of DC arc furnace technology, as applied to steelmaking, has steadily progressed. At present, there are three DC arc furnaces in commercial operation in the steel industry. Two of the furnaces are located in the United States, one at Nucor's Darlington Plant in South Carolina, and the other at the Florida Steel plant in Tampa, Florida. Both of these furnaces are single electrode furnaces. The third furnace, located in France at the Societe Metallurgique D'Esault (SME) plant, is equipped with three top electrodes and three water cooled hearth electrodes. A new commercial DC furnace is under development at the Cognes Steelworks, Aosta, Italy, however, little information is available on this plant.

It has been reported that a large DC steel making furnace will start operation in Japan in 1988.

The only non-ferrous commercial DC furnace operation is located at the Middleburg steel plant in South Africa. It was designed to produce high carbon ferrochrome from chromite fines. Operating data are not available from this plant. Inco Ltd. has successfully operated a 150 kVA furnace in which fines were fed through the single graphite top electrode. A 1.2 MW pilot plant unit has been commissioned recently by Inco Ltd. at the Port Colborne plant; however, operating data are not available as yet. It has been reported that a DC arc furnace will be constructed in West Germany for recovering precious metals from automotive catalysts.

Advantages

The major advantages of DC as compared to AC arc furnaces in the steel industry are:

a) Reduction in electrode consumption, 50 - 60%.

b) The disturbance (flicker) to the utility system is reduced by about 30 to 50%. This could be significant for plants with weak power supply systems.

c) Reduced noise level in the plant. This has been reported in the literature, but very little difference between the noise level emanating from DC and AC furnaces was observed during the plant visits.

d) More uniform temperature distribution in the furnace which results in lower sidewall refractory consumption.

e) Improved control of input power profiles with DC furnaces.

Advantages of DC over AC furnaces have not as yet been demonstrated in the non-ferrous industry on a commercial scale. However, higher furnace productivity has been claimed for operations on the pilot plant scale along with the ability to successfully smelt fine materials.

Limitations

It has been suggested by the electric furnace designers that the maximum size of a single electrode DC furnace is limited to approximately 60MW or 80 tonnes, because the diameter of the largest commercially produced graphite electrode is 700 mm (28 in). AC furnaces range up to 130 MVA. The use of multi electrode DC furnaces overcomes this limitation, but with marginally reduced savings in electrode consumption.

The capital cost of a DC furnace is higher than that of an AC furnace installation. The main reason for this is that the DC power supply costs more than an AC furnace transformer. Some of the higher power supply cost is offset by the fact that only one rather than three electrode arms and ancillary equipment are required by the DC furnace.

The bottom electrode is seen as the "Achilles Heel" of the DC electric furnace. This weakness is gradually being overcome through the experience gained in commercial steelmaking operations and the changes made as a result of this. The hearth life is much more critical in non-ferrous smelting operations, since these furnaces are required to operate continuously for several years without a shut down. Steel making operations, by contrast, are batch operations. Insufficient information is available to predict the hearth life for sulphide smelting operations. It is, therefore, not known whether hearth life will be a limiting factor to the application of DC furnace technology to sulphide smelting.

Future Outlook for DC Furnace Technology in Ontario

The metallurgical industry in Ontario is open minded to the adoption of DC arc furnace technology. The steel industry, in particular, will consider conversion of AC to DC furnaces or the installation of new DC furnaces when the confidence level in the technology has been fully demonstrated and when an economic advantage of a DC over an AC furnace can be confirmed. The economic decision is very site specific.

The main economic incentive for a DC furnace installation is found in the cost savings of electrode consumption. It appears that from an electrical standpoint the DC arc furnace is somewhat preferable to an AC furnace. However, this preference alone is likely insufficient to outweigh the extra cost. In areas where a weak electrical mains supply makes flicker compensation mandatory the economics could favour the DC arc furnace.

It has been suggested that the cost of graphite electrodes will continue to decrease since electrode costs are tied to oil prices. Also, the electrode consumption in AC furnace operations continues to decrease as a result of larger higher-powered furnaces, shorter heat times and water cooled permanent electrodes and water sprayed electrodes. As a result, the savings in electrode consumption (kg/tonne) between an AC and DC operation will decrease, making conversion from AC to DC less attractive. There appears to be a future niche for DC steel making furnaces in the range of up to 60 MVA.

There is at present insufficient information available on the basis of which DC furnaces for the non-ferrous industry can be justified. Bench scale and pilot plant test work is required to determine how potential advantages of DC furnaces over AC furnaces can be commercialized.

Potential new applications of DC furnace technology in the non ferrous industry are slag cleaning, treatment of fines, process intensification and smelting of alumina.

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To Mr. P. Vyrostko
Manager
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DC FURNACE TECHNOLOGY IN THE METALLURGICAL INDUSTRY

1. INTRODUCTION

Advances in the field of power thyristor technology has lent fresh impetus to the development of the direct current (DC) arc furnace for the metallurgical industry. Since 1972, there has been a widening international interest in this development. The DC furnace has the potential to overcome the limitations of the modern, efficient alternating currents (AC) arc furances, namely the high electrode consumption costs, utility system disturbances and furnace noise.

This state-of-the-art report combines an up-to-date review of the literature with the knowledge gained from visits to DC furnace operations and contacts with suppliers. The report further contains current Ontario electric furnace plant descriptions and general industrial opinions as to the applicability of DC technology in today's metallurgical plants.

2. CURRENT STATUS OF DC ARC FURNACE TECHNOLOGY

ASEA, Brown Boveri (BBC), Krupp, GHH, IRSID[a], and Clecim are the main driving forces behind the development of the DC arc furnace.

The first DC arc furnace was operated in Sweden as early as 1972. It produced 1000 tonnes of iron over a three year period. A number of furnaces were operated, primarily in Sweden, on DC for a period of time and then returned to AC duty. The reason for changing the furnaces back to AC was that they were used as experimental furnaces to develop design information.
Table 2.1 summarizes the DC arc furnace plants currently in operation as well as the plants which have been operated on DC for a period of time in the past. Information on DC arc plants in either Japan or Russia could not be found in the literature. A contact in Japan[40], however, indicated that the first Japanese DC furnace is to go into production in early 1988.

a Institu de Recherces de La Siderurgie Francaise.

TABLE 2.1

SUMMARY OF DC FURNACE OPERATIONS

COMPANY AND LOCATION	OPERATION START UP	OPERATION SHUT DOWN	PRODUCT	TONS	MVA	COMMENTS
Operating Plants						
NUCOR STEEL Darlington, SC, U.S.A.	Jan 1985	--	Carbon Steel	30	12	
FLORIDA STEEL CORPORATION Tampa, FL, U.S.A.	Mar 1985	--	Carbon Steel	33	11	
SMS SCHOLEMANN - SIEMAG AG Busch Huetten, West Germany	May 1982	--	Carbon Steel	12	6	
SOCIETE METALLURIQUE DE L'ESCAUT (SME) Trith, St Leger, France	Dec 1984	--	Carbon Steel	95	60	
MIDDLEBURG STEEL & ALLOY Krugers Dorp, S. Africa	1984		High Carbon Ferrochrome	N/A	20	
Plants with Intermittent Operation						
GULLSPANG, Sweden	1981	--	FeW	4	1.2	1,800 Tons
GULLSPANG, Sweden	1982	--	Recovery of Mo, Co & Fe Si	6	2.0	1,300 Tons
Experimental & Pilot Plants						
INCO, Port Colborne, Can.	1987	--	Pilot Plant	2	1.2	--
IRSID, France	?		Pilot Plant	6	3	--
MEFOS, Sweden	1972	1975	Iron	7	4.5	1,000 Tons
KANTHAL, Sweden	1972	1976	Alloy Steel	30	9	8,000 Tons
DOMNARVET, Sweden	1977	1979	Carbon Steel Iron	30	11	3,500 Tons
AVESTA, Sweden	1983	1984	Stainless Steel	55	8	17,500 Tons
CENTRO SPERIMENTALE METALLURGICO, Rome	1982	--	Pilot Plant	3.5T	N/A	Italian Experiment
COGNE'S STEELWORKS, Aosta, Italy	1984	--	Experimental	50T	N/A	

...2

Summary of DC Furnace Operations (Cont'd)

COMPANY AND LOCATION	OPERATION		PRODUCT	TONS	MVA	COMMENTS
	START UP	SHUT DOWN				
ITALY TORINO	N/A		Experimental	6T	2.4	2 Electrode, No Bottom Electrode
New Plants Under Construction						
GERMANY, SMELTING OF AUTOMOTIVE CATALYST	1988	N/A	Platinum			N/A
JAPAN	1988	—	Steel	N/A	N/A	N/A

(MT19)

At present two DC arc scrap melting furnaces are operated in the U.S., Nucor Steel in Darlington S.C. and Florida Steel in Tampa, Florida. Another scrap melting DC furnace is operated in France by SME and it is believed that there is a smaller unit still in operation in West Germany. The Middleburg Steel and Alloy Corporation has operated a high carbon ferrochrome plant in South Africa since 1984. The literature also shows that a few small specialty steel and alloy DC arc electric furnace plants are operated on an intermittent basis. Inco, IRSID (France) and CSM (Italy)[b] have pilot plants. The IRSID and CSM pilot plants are designed to melt steel scrap, whereas the Inco pilot plant has been designed primarily for melting and smelting fines fed through a hollow electrode into the furnace bath.

Table 2.2 summarizes the technical data for the commercial scale DC furnaces. Information is not available for the Italian pilot plant, and the information for the Middleburg HCFC plant is sparce, both of which are active facilities as noted in Table 2.1.

One reference[2] notes that a DC furnace is under construction in Germany for smelting spent automotive catalyst to recover precious metals. It could not be confirmed if this project has been completed.

Two types of power supply systems can be used for DC arc furnaces. The circuit diagrams are shown in Figure 1. The power supply system (A) is being used to retrofit AC furnaces for the simple reason that it can utilize the existing furnace transformer. A thyristor controlled rectifier and a DC choke are added to complete the conversion to DC.

3. COMPARISON BETWEEN DC AND AC ELECTRIC ARC FURNACE OPERATIONS

The comparison between DC and AC arc furnace operations is primarily based on literature data supplemented by information from suppliers and visits to plants where the furnaces are in operation. The information is current, up to the latter part of 1987.

3.1 Electrode Consumption

There is generally agreement that the electrode consumption is significantly lower for DC than for AC operations as shown in Table 3.1.

b CSM = Centro Sperimentale Metallurgico.

TABLE 2.2

SUMMARY OF COMMERCIAL DC ARC FURNACES

Company and Location	Furnace Rating -Transformer -Capacity -Shell Dia.	Electrode Dia. and Arrangement	Hearth Design	Tap to Tap Time	Electrode Consumption kg/Tonne		Power Consumption kwh/Tonne		Oxygen Consumption Nm^3/Tonne		Productivity for DC Furnace	
				Mins	AC	DC	AC	DC	AC	DC	Tonnes/hr	Tonnes/hr
Nucor Steel Darlington, SC	12 MVA 27 tonnes 3.8 m	Single 460 mm	-MAN/GHH -Pin Type -Conducting Hearth	129	5.25	2.1	527	509	203	12.5	12.3	26.4
Florida Steel Tampa, Florida	11 MVA 30 tonnes 3.8 m	Single 460 mm	-ASEA -Conductive Refractory	120	5.5	2.0	513	504	N/A	N/A	13.2	26.4
SME, Celcim France	60 MVA 86 tonnes 5.8 m	Three 500 mm	-IRSID-CELCIM -Three Water Cooled Bottom Electrodes	80	3.75	2.2	N/A	500	N/A	17.6	55.2	73.6

(MT19)

N/A - Not available.

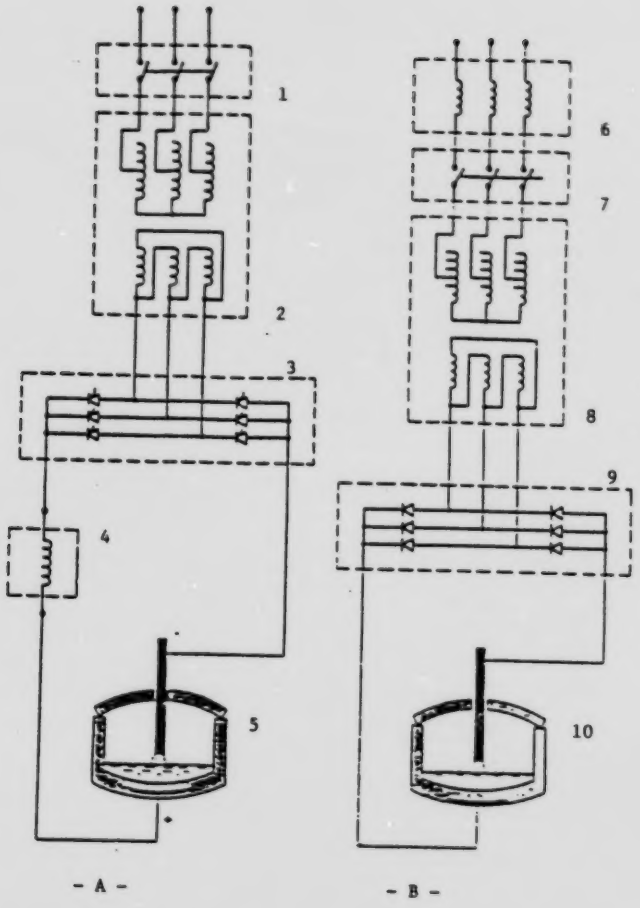


Figure 1 Circuit diagrams for DC arc furnaces power supply systems:

With thyristor convertor:

1 Furnace main circuit-breaker
2 Furnace transformer
3 Thyristor-controlled power convertor
4 DC reactor
5 DC furnace

With diode rectifier:

6 High-voltage reactor
7 Furnace main circuit-breaker
8 Furnace transformer
9 Uncontrolled diode rectifier
10 DC furnace

TABLE 3.1

ELECTRODE CONSUMPTION

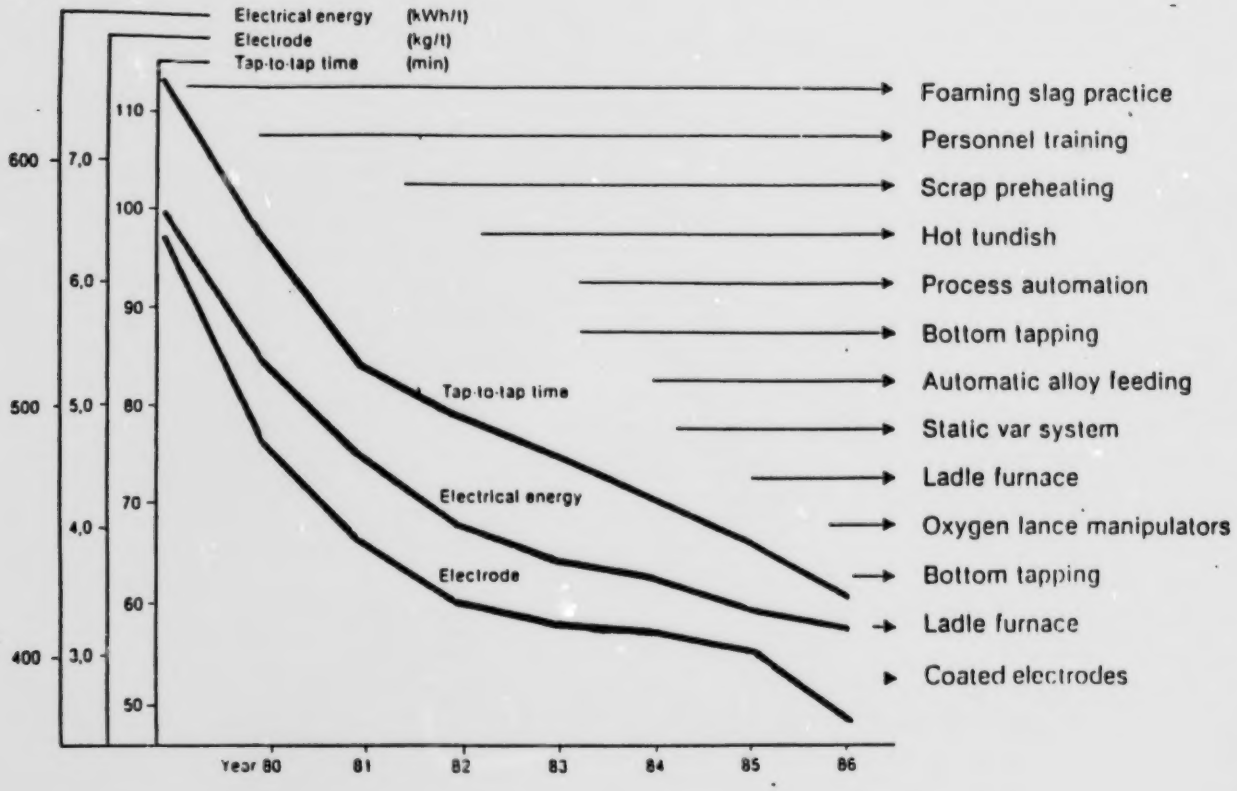
	kg/tonne (lbs/ton) AC Operation	kg/tonne (lbs/ton) DC Operation	
Nucor	5.25 (10.5)	2.1 (4.2)	
Florida Steel [7],	5.50 (11)	2.0 (4.0)	
SMS Schloemann [7],	6-7 (12-14)	1.8 (3.6)	
SME [7],	3.75 (7.5)	2.2 (4.4)	
Irsid	6 (12)	1.5 (3)	(calculated)

The reduction in electrode consumption achieved by converting from AC to DC ranges from 50 to 60 percent. However, it should be noted that the electrode consumption in AC furnace has also been decreasing as shown in Figure 3.1-1, and is approaching a level of 3 kg/tonne. As a result of this, the absolute saving in electrode consumption by converting from AC to DC is decreasing, and hence the potential saving in operating cost.

There is also a small saving to be realized in electrode inventory cost. If a single DC electrode is used. The diameter of the electrode will be 1.6 times the diameter of an electrode from a three electrode furnace. Therefore, if three electrodes with a unit diameter of 1.0 are used, their volume will be 2.35 units, whereas the volume of one electrode with a diameter of 1.6 is 2.01 units. The saving in electrode volume is therefore 14.7 percent. This could be quite significant because of the high unit cost of electrodes.

The improvement in electrode consumption is a result of lower surface wear of the single DC electrode versus the 3 electrode AC system. Electrode consumption occurs at the tip and on the vertical surfaces. Replacing three electrodes with a single electrode will reduce the surface consumption by about 67%. The temperature of the anode in an arc is always considerably higher than the cathode. In the DC furnace the top graphite electrode is always the cathode, consequently its temperature is lower and the tip consumption is less. The hottest part of the arc is on the bath. In addition, theoretically, there should be fewer electrode fractures and stub losses. This results from lower vibrations on the electrode supports, as there are no electro-dynamic forces acting on the electrodes in the DC furnace, which normally lead to electrode fractures. The target electrode consumption for DC furnaces is about 1.5 kg/tonne (3.0 lbs/ton) of liquid steel.

Figure 3.1-1 Evolution of Productivity, Electrical Energy and Electrode Consumption for Very Efficient AC Operations



3.2 Refractory Consumption

The expectations of lower overall refractory consumption in DC arc furnaces as compared to AC arc furnace operation has not been fully realized to date[2], . Both Nucor and Florida Steel report that the refractory costs for their AC and DC furnaces are approximately the same with a slight advantage to D.C. , . However, Clecim claims[C] a substantial savings in refractory primarily due to the savings in gunning materials for the sidewall.

C Visit to JME - Clecim's North American representative.

DC furnace operation has reduced the sidewall refractory consumption, but it has led to higher bottom refractory wear. SME[7] also states that initially roof life was shorter for DC than for AC operations. This has not been observed at either the Nucor or Florida Steel operations. The reason for this can be most likely found in the furnace design. When additional water cooling was added to the roof at SME, the roof life problem was solved. Nucor and Florida Steel use a single electrode, whereas SME has designed their furnace for a three electrode operation.

Table 3.2-I compares the relative refractory consumption for AC and DC arc furnace operations and Table 3.2-II gives the reported refractory consumptions.

TABLE 3.2-I

RELATIVE REFRACTORY CONSUMPTION

	AC	DC
Sidewalls	High	Low
Bottom	Low	High
Sidewall gunning	High	Low

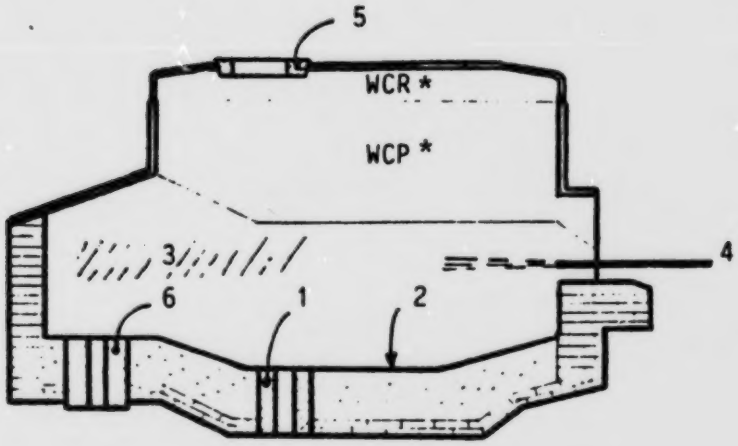
TABLE 3.2-II

REFRACTORY CONSUMPTION KG/TONNE (LBS/TON)

	AC Operation	DC Operation
Nucor Steel (45)	7 (14)	7 (14)
Florida Steel (2)	6 (13)	6 (13)

Clecim[9] compares the refractory consumption for AC furnaces in Japan and Europe to the refractory consumption in DC furnaces by furnace area as shown in Figure 3.2-1.

Figure 3.2-1
DC/AC Refractory Consumption



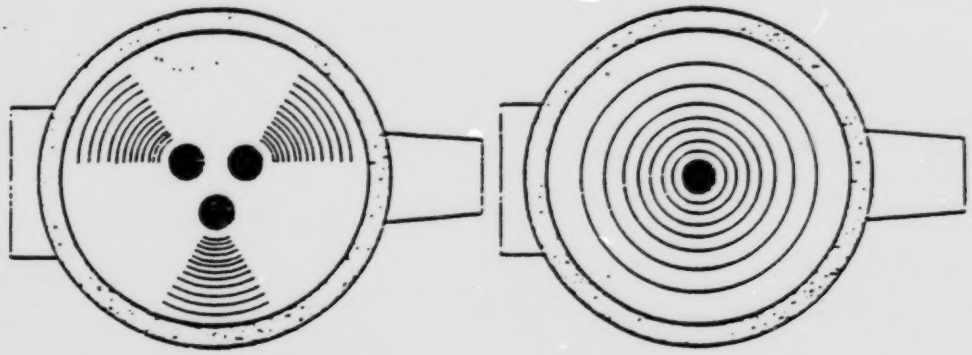
	AC kg/t Japan	AC kg/t Europe	DC kg/t
1. SPECIAL REFRACTORY	/	/	0,08
2. HEARTH	2	1,5	1,5
3. WALLS, SLAG ZONE		0,5	0,25
4. GUNNING	8	2,0	0,20
5. ROOF	0,5/0,2	0,2	0,4
6. TAP HOLE	/	0,05	0,05

* WCR - Water Cooled Roof
* WCP - Water Cooled Panels

The comparison in Figure 3.2-1 appears to be based on ideal assumptions with respect to hearth refractory consumption. It shows higher roof refractory consumption for DC than AC furnaces.

The reason for the lower sidewall refractory consumption is shown in Figure 3.2-2

Figure 3.2-2 Sidewall Refractory Consumption[3]



Uneven heat distribution pattern in 3-phase AC furnace.

Uniform heat distribution from central, vertical arc in DC furnace.

In an AC furnace the three arcs repel each other by magnetic forces. A maximum heat load zone is thus created in front of each electrode, leading to increased refractory attack. Since the DC furnace operates with one central vertical arc, the heat load on the wall is uniform and the hot spot problem is effectively eliminated. Side wall attack is also lower in the three electrode DC furnace[9] because the arcs do not repel each other and thus arc flaring is eliminated. The three arcs are effectively focused toward the center of the furnace.

The furnace hearth is still the weakest link in the DC furnace operation. Nucor Steel[45] reports a furnace hearth life of 9,090 tonnes (10,000 tons) of steel at a cost of $2.20/tonne ($2.00/ton) of steel. They expect to increase the hearth life to 12,270 tonnes (13,500 tons). Florida Steel[2] has recently increased the bottom refractory life to 14 weeks by changing the conducting hearth refractory brick to a 20% carbon-sintered MgO brick. Florida Steel has reported that the wear on the hearth is not uniform. The wear is more pronounced at the center of the hearth directly below the centre electrode. The area affected is circular and twice the diameter of the single

electrode. This area is repaired with a gunning mix as required. Although not effecting the furnace downtime, the conductive gunning materials are expensive. Consideration is being given to replacing the conducting bricks in this area with more wear resistant non-conducting bricks.

The conducting bricks are weaker than the standard refractory. As a result of this, structural failures occurred at the furnace "knuckle" (where the side walls meet the bottom). To overcome early refractory failures, the outer five rings of the conducting bricks of the hearth were replaced with stronger non-conducting bricks. The problems appear to have been solved.

It should be noted that both the Nucor and Florida Steel DC furnaces are operated on a 15 to 17 shift per week cycle which makes it possible to carry out major refractory repairs on the weekend. If these furnaces were to be operated on a 21 shift per week basis, their availability would be expected to be lower than those of AC melting furnaces. ASEA claims, however, that some of the refractory wear problems are created by the thermal cycling of the refractory when the furnace is shut down and re-started on each weekend.

To operate on a continuous basis, consideration should be given to having multiple shells in order to minimize the down time when carrying out major refractory repairs. The second shell would be situated beside the one in operation such that the electrodes could be swivelled to the new furnace shell. This would be an added cost factor for the DC approach.

SME France[20] claims a furnace bottom life of 6 months, but do not report any detail on repair work schedules. It must be pointed out that Nucor and Florida Steel use conducting pins and conducting refractory respectively as their bottom electrode-hearth. SME is using water cooled steel billets, and therefore in effect a water cooled hearth which reduces hearth refractory wear.

ASEA, Brown Boveri and Krupp have deliberately avoided the water cooled hearth design because of their concern that water cooling could lead to an explosion in case of a furnace break out. SME has operated their furnace for over 13months without reporting an incident. This appears to demonstrate that a safe water cooled hearth can be designed.

To improve the economics of the DC arc furnace, improvements in the conducting hearth must be developed. It is true to say that all commercial operations are still in a developmental stage of operation with respect to the furnace hearth.

3.3 Productivity

Insufficient data is available on DC furnace operations to permit a valid comparison with AC operations.

ASEA[11] has estimated that in the case of DC operation 72% of the available electrical power is transferred to the melt versus 65% in an AC operation. This would imply a potential improvement in energy utilization of 7% and thus in turn a 7% increase in productivity in favour of DC. It is also claimed that a DC furnace operation[19] can operate at full power during meltdown. In most AC furnace operations, the power input is increased as the melt proceeds.

The operating results thus far reported by Nucor Steel[45] have not shown a higher productivity for the DC furnace when compared to the sister AC furnaces. In fact, the productivity of the DC furnace was 7.5% below that of the AC furnaces. The lower productivity reported for the DC furnace is not inherent in the design of the furnace. The main reasons for the lower DC furnace productivity were:

- the AC furnace was equipped with oxy-fuel burners,
- less oxygen was used in the DC furnace as there were fewer cold spots requiring supplementary heat,
- the peak power input was held to a lower level than used on the AC furnace, and
- the time required to develop DC furnace operating practice.

Productivity data for operating DC furnaces are reported in Table 3.3-1.

TABLE 3.3-1

DC FURNACE PRODUCTIVITY DATA

	Nucor[1]	Florida Steel[2]	SME[7]
Tap to Tap Time, mins	129	120	80
Transformer Rating, MW	12	11	60
Tonnes/Tap	26.4	26.4	73.6
Productivity, tonnes/hr	12.3	13.2	55.2
Power Rating KW/tonnes capacity	444	367	698

A valid comparison between productivity of AC and DC furnaces can be made only when all the many factors influencing productivity are taken into

account. Currently AC furnaces are generally equipped with larger transformers than the developmental DC furnaces; AC furnaces are also powered at up to 700 kW per tonne of furnace capacity. Only the SME DC arc furnace has the same specific power rating.
The power rating for Nucor Steel and Florida Steel are 444 and 367 kW/tonnes respectively. The use of oxygen, oxy-fuel burners and scrap preheaters also play an important role in determining furnace productivity. This technology is well developed and applied to many of the AC furnaces. So far it has been applied to a limited extent only to the DC furnaces. If fully applied, it will also increase their productivity. Figure 3.1-1 shows the increase in productivity for AC furnaces over time and the application of improved furnace technology.

3.4 Specific Energy Consumption

Firm conclusions cannot be drawn from the data available concerning differences between the specific energy consumption between AC and DC furnaces because of the many factors entering into such a study. The differences appear to be small but in favour of DC operations.

The most reliable study carried out to date was done by the Centre for Metals Production(CMP)[44] which compares the electrical energy consumption for identical AC and DC arc furnaces at the Nucor Darlington plant in South Carolina. The electrical energy consumption for the DC furnace is lower by 3.3% as compared to that of the AC furnace in spite of the fact that the oxygen blowing time for the DC furnace was 24 minutes as compared to 40 minutes for the AC furnaces.

Florida Steel[2] reports also a reduction of 1.8% in electrical energy consumption for the DC operation based on the results of 50 heats made in comparable AC and DC furnaces employing similar melting practices.

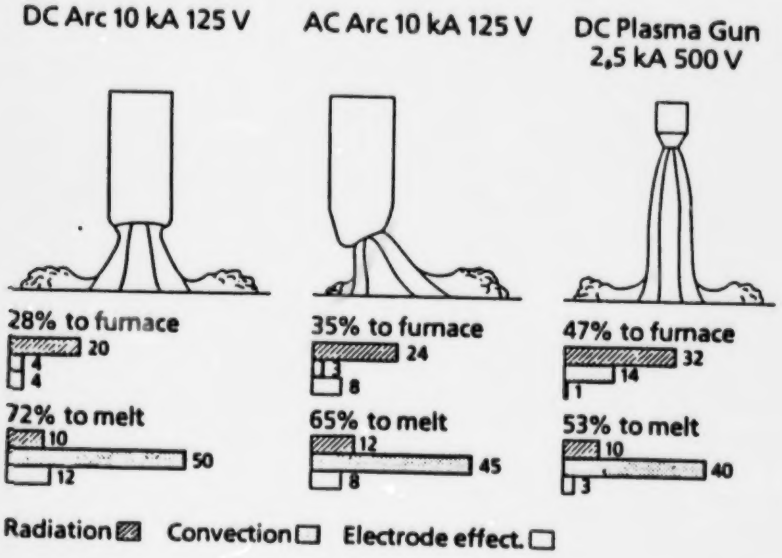
TABLE 3.4-1

	Energy Consumption Kwh/tonne	
	Nucor Steel	Florida Steel
AC Operation	527	513
DC Operation	509	504

Avesta[30] states that the slightly higher energy consumption experienced for the DC operation is the result of operating procedures employed. SME reports an average energy consumption of 572 kWh/tonne with a record of 506 kWh/tonne at an oxygen consumption of 16 Nm^3/tonne. They do not state whether oxy-fuel burners were used.

John Persson of Lectromelt [31] expects a higher energy consumption for DC furnaces because of the inefficiencies inherent in the conversion of AC to DC. Other authors claim that this is counterbalanced by the inductive power losses experienced in the AC system. Stenkvist of ASEA [11] expects a lower energy consumption for DC furnace operations, since 72% of the electrical input is transferred to the melt as compared to 65% in AC furnaces as shown in Figure 3.4-1.

Figure 3.4-1 - Comparison of melting power distribution for DC, AC arcs and a DC plasma gun.



3.5 Furnace Operation Reliability

Little information can be found in the literature with regard to the relative reliability of AC and DC furnaces. In general, there appears to be little difference between the reliability of AC and DC furnaces, with the exception that the furnace hearth of the DC furnace may be subject to unexpected repairs.

The main items to be considered when evaluating relative furnace operation reliability are:

- Electrode hoist and control system
- Rectifier
- Furnace bottom

Electrode Hoist and Control System

All DC arc furnaces except the SME furnace use a single rather than three electrode hoist and control system. Since the electrode hoist is a well developed and reliable furnace item, it is expected that using one rather than three systems will not greatly contribute to the furnace operating reliability.

Rectifiers

Modern rectifiers are considered to be reliable. No reports have been received to date that rectifier failure has disrupted operations.

Furnace Bottom

The conducting furnace hearth is the weakest part of the DC furnace. Frequent repairs are required for conducting or pin type hearths. Catastrophic failures have not been reported for the ASEA, Brown Boveri or SME hearths. DC furnace hearths require in general more frequent inspection and repair than AC furnace hearths, but they appear to be essentially reliable.

Florida Steel/[2]/ reported an 8% unscheduled downtime during initial operation but this has recently been reduced to 1% or one day in six months of operation as a result of changes to hearth design.

3.6 Environmental

It is generally agreed that the DC furnace operation is quieter than AC melting[1 2 3 7 8 19 20]. The lower noise level leads to a more desirable operating environment. ASEA[3] reports a noise level of 90 dBA at melt down, SME[7 20] reports a noise level of 110 dBA in the furnace enclosure which is 5-10 dBA below the AC operation. The noise level in the control room is 75 dBA. It has been reported[27] that the long-time mean value of noise pollution of a DC furnace is below that of a comparable three phase AC furnace. However, depending on scrap quality, the peak values are of equal magnitude. It is suspected that the lower mean noise value is related to the absence of polarity changes and to the fact that a molten pool is more rapidly formed under the single electrode due to the higher power input density.

The working atmosphere around a single electrode furnace is also expected to be cleaner since the furnace can be made tighter than a three electrode furnace.

It has been suggested that a DC furnace can be used for the destruction of PCB's.

3.7 Product Quality

The literature does not reveal any quality difference between steels produced in AC or DC furnaces. The current trend towards the adoption of ladle metallurgy stations in combination with electric arc furnaces is the technology that has the greatest effect on steel quality. The use of AC heated ladle metallurgy furnaces will continue to spread in steel plants because of the demand for higher quality steel with a wider range of physical properties.

Florida Steel[2] claims that they are able to obtain a higher yield of alloying elements in their DC operation. Although difficult to understand, it is most likely related to the use of oxygen during melt down in an AC furnace rather than the type of current used.

Nucor Steel claimed that there was no difference in the quality of the steel produced in either the AC or DC furnace.

There are conflicting claims[14 23] concerning steel bath stirring in DC furnaces. It is indicated[14] that there is better homogenity of the melt with DC in one case with the exact opposite claimed in another source.[23]

3.8 Capital Costs

The capital costs required for the installation of a new DC electric furnace range anywhere from 15%[22] to 35%[12] higher than the cost of an equivalent AC furnace.[12] On the other hand, the conversion of an AC furnace to DC costs 30% less than building a new AC furnace, or about half the cost of building a new DC furnace.

No firm capital cost figures are available. Also, as shown later, the estimate of the payback period for the additional capital requirement for DC furnace installations varies widely. Most of the payback estimates are based on the reduction in operating cost achieved by reducing the electrode consumption. The payback time will very much depend on the actual reduction in electrode consumption and electrode cost. Savings in refractory cost are currently minimal as shown in Section 3.2 and therefore will not affect the calculation.

It is claimed by Nucor[19] that a furnace converted from AC to DC can have a three year payback based on electrode saving. Brown Boveri[12] had stated earlier that the increased cost of building a new DC furnace could be amortized in one year. The company also stated that the conversion cost from AC to DC could be amortized in two years.

Information on conversion costs from AC to DC were not made available during the visits to Nucor and Florida Steel. Nucor indicated that their payback on capital will be about 3 years. Florida Steel claims a cost advantage of the DC over their AC furnace of $US 9.00/tonne of metal, mainly as a result of electrode savings with minor contributions from energy and refractory savings.

Although various claims with regard to capital cost have been made in the literature, no hard figures are available. The only way in which reliable figures can be obtained is to request firm quotes from suppliers for equivalent DC and AC furnace installations.

3.9 Maintenance and Labour Requirements

No significant difference in maintenance cost and labour requirement is expected between a DC and an AC electric furnace shop.

The significant maintenance issue of DC furnaces centers around the furnace bottom. The French[7] have stated the bottom can have a life of six months of operation with water cooled billet electrodes. Great attention has been paid to the design of the water cooling system. Clecim[20] reported that the bottom billet life was about 150 heats. Nucor's[19] furnace required bottom lining replacement after 9,090 tonnes (10,000 tons) of production, with improved bottom ramming, this may be extended to about 12,270 tonnes (13,500 tons). Nucor expects that a new pre-assembled plug for the bottom contact will permit replacement in a hot furnace which will further improve maintenance cost and time. The current cost for bottom maintenance at Nucor[45] is about US$1.43/tonne of steel (US$1.30/ton) produced.

The single electrode DC system inherently requires less maintenance[33] on the electrode arm, clamps and on the electrode positioning drive as compared to the three electrode AC systems. The on-load tap changers also require less maintenance and there are less dynamic stresses on the furnace with the DC set up.

The literature gives no indication of any changes in labour requirements for operating a DC furnace. There are no apparent operating differences[2] between DC and AC furnaces, the only minor exception maybe found in electrode arm and furnace bottom maintenance labour. In view of the more frequent and extensive furnace hearth repairs, maintenance staff requirements are most likely higher for a DC than an AC furnace operation. The differences in overall labour requirements would be minor.

3.10 Furnace Start Up

Starting a DC furnace from a cold start appears to be somewhat more difficult than starting an AC furnace. Problems can be experienced if the conductive hearth is covered with a layer of slag[30]. All DC furnaces are operated with a hot heel during normal operations.

Cold Start - Nucor Steel[1] starts a furnace with a new hearth lining by first heating the lining with a gas torch and then charging shredded scrap: a 70 minute power schedule is used to bring the furnace to full power. For a weekend shut down a minimum amount of metal is left in the furnace. A small amount of scrap is charged, and an arc struck for about one minute to ensure good electrical contact with the bottom. The furnace is then left to soak to minimize thermal stresses. A 20 minute power schedule is used to bring the furnace to full power.

Florida Steel[2] charges 15,000 lbs of shredded scrap to the furnace, the door burners are operated for approximately 30 minutes to create a molten heel in the furnace. A low current arc is struck for a couple of minutes. If arcing is normal, the furnace is put on full power. If not, more shredded scrap is charged and the pool of molten metal increased by operating the door burner.

When SME shuts down, a small amount of liquid metal is left in the furnace bottom. To ensure sound electric contact with the three steel billet electrodes during the next start-up and avoid an insulating slag cover, three steel spiders are driven down through the heel. This essentially extends the electrodes to the surface of the heel and avoids any insulation affects from a solidified slag covering. The SME furnace can also arc between two of the three electrodes to start-up.

Hot Start - All furnaces are operated with a molten heel. Florida Steel[2] and Nucor use a 1 to 4 ton heel whereas the SME furnace uses a 14 ton heel.

3.11 Effect on Electric Power System-Flicker

The proponents of D.C. arc furnaces[1 5 7 19] clearly indicates a reduced amount of flicker on the power supply lines. The improvement over the A.C. system ranges from 25 to 50 percent with accompanying lower harmonics. This characteristic along with electrode savings and some refractory savings are the key advantages of the D.C. furnace.

3.12 Maximum Furnace Size

The maximum size of a single electrode DC furnace[3] is limited in part by the maximum size of the carbon electrodes produced. At present the maximum size, 700 mm dam (28 inch), electrode, would permit a furnace of 90 MW, a speculation for the time being. Nucor[19] and Brown Boveri[23 26] suggest a maximum power of about 60 MW based on 120 conducting pins in the furnace bottom and a 700 mm single electrode. Depending on the design, this will support a 70 to 80 tonnes furnace and be considered as an ultra high powered furnaces by today's standards.

There are freedoms to increase the powering of a DC furnace by either going to a two electrode oval furnace[23] or utilizing the three electrode furnace developed in France.

Replacing the single electrode by two or even three electrodes will marginally increase the electrode consumption. Also, employing more than one top electrode, will also increase the sidewall refractory consumption as compared to that experienced in the uniform heat pattern of a single electrode furnace.

A representative of Clecim stated that the electrode and refractory consumption of their furnace is comparable to that of the single electrode furnace (private communication).

4. EVALUATION OF DIFFERENT DC ARC FURNACE HEARTH DESIGNS

The part of the DC arc furnace technology requiring the greatest future development is the hearth design. The reliability and maintenance cost of the hearth is perhaps the single most important hurdle in the acceptance of the DC furnace.

There are currently three basic designs being used. These are: a hearth constructed of conductive refractory bricks from ASEA (Figure 4.1), a hearth with air-cooled steel pins embedded in the refractory from Brown Boveri Corporation (Figure 4.2), and a hearth with multiple water-cooled steel billets protruding through the refractory bricks from IRSID and Clecim. (Figure 4.3). All three concepts have had their own individual problems but all are in commercial operation.

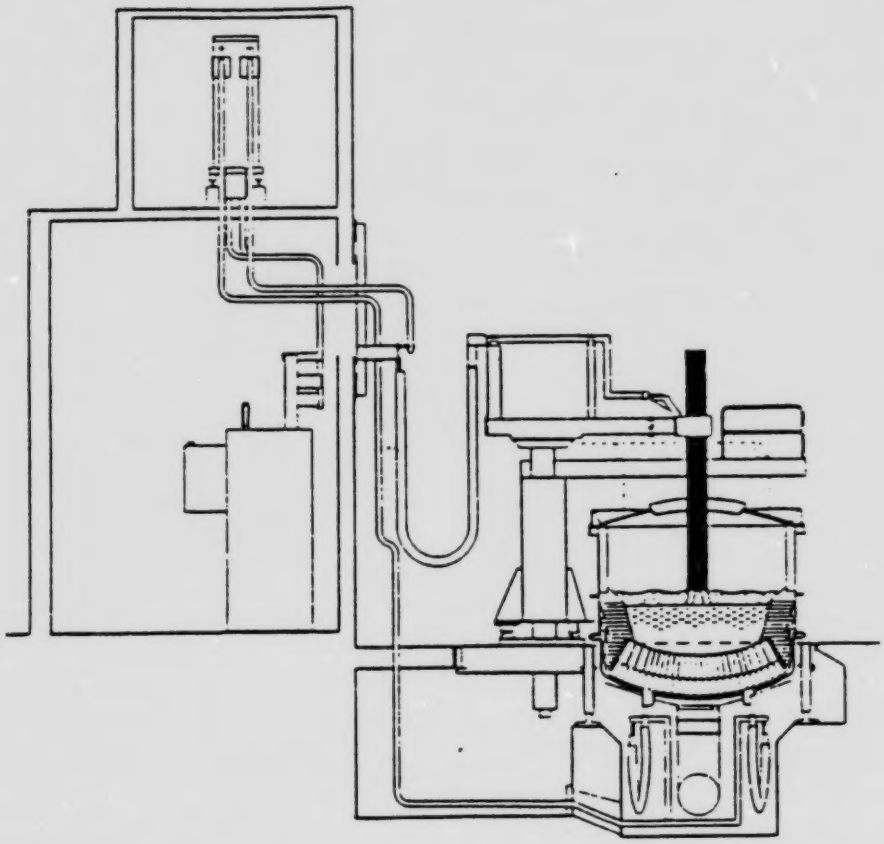
ASEA

The ASEA design, operating at Florida Steel Corporation, utilizes conducting refractory bricks in the hearth. There is a large, circular copper plate, divided into four sections which are bolted to the furnaces bottom and serve as the contact plate. Each section of the copper plate has a terminal extending through the bottom shell with a water cooled power cable connected to each terminal. On top of the copper plate is the electrically conductive hearth, consisting of magnesite graphite refractory. The higher thermal conductivity of this refractory material dictates the use of a cooling system more effective than natural convection. An air duct with an axial fan has been installed under the furnace. The furnace bottom temperature is monitored by 12 temperature sensors. Typically, the temperature ranges between 150°C and 200°C.

A number of different refractories have been tested. Although in all cases, a permanent safety lining consisting of 10% carbon burned magnesite-graphite bricks has been used. The type of brick used here incorporates an ideal combination of high electrical and relatively low thermal conductivity. A two layer wear lining on top of the back-up lining is made up of bricks having carbon contents between 10 and 20%, and is subject to periodic replacement. Thesebricks are a sintered magnesite containing fused magnesia. The purity of the magnesia bricks tested varied from 95.8% and 99% MgO. The service life of the bottom wear lining had been about 4 weeks.

Figure 4.1

ASEA Lay-out of the DC Furnace Installation at Florida Steel Corporation.



A recent improvement in wear lining performance, to 14 weeks (761 heats), was achieved with a 20% carbon, 99% purity sintered magnesia brick. The present (Dec./87) average hearth life is reported to be about 300-400 heats. Improved maintenance and repair practices are also partly responsible for the improved bottom lining life.

Significant design changes have also been required since the initial installation. The outer edge of the furnace hearth (area which supports the side walls) was failing prematurely. This was a result of the lower structural strength of the conducting bricks as compared to the standard high temperature insulating bricks. The outer five rows on the hearth were therefore replaced by non-conductive insulating bricks, which alleviated the problem without affecting operating parameters.

Florida Steel has also reported extraordinary wear on the hearth directly below the top electrode. The wear area was twice the diameter of the upper electrode and was about twice that of the general bottom wear rate. This problem was overcome by ramming with high carbon materials on weekend shutdowns. Florida Steel and ASEA are presently considering the replacement of the central bricks in the bottom wear area with non-conducting insulating bricks.

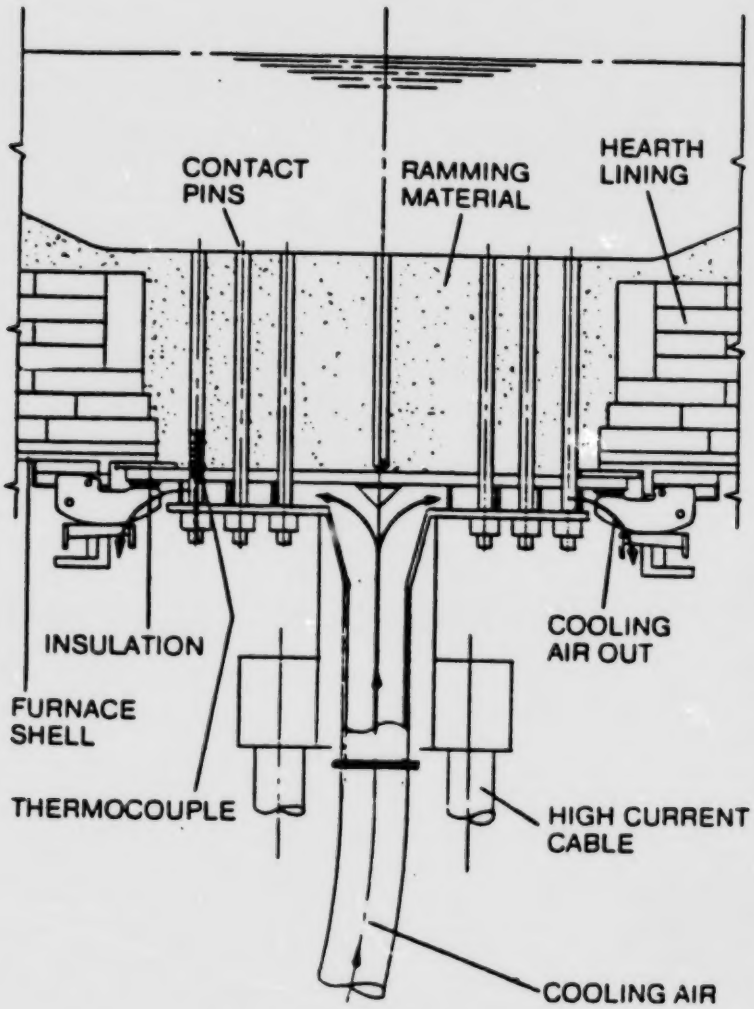
The five day, fifteen shift operation of the furnace at Florida Steel provides adequate time to carry out refractory repairs. However, this routine start-up after weekend shutdown causes severe thermal cycling. The resulting thermal stresses greatly reduce the service life of the furnace refractory system. While the weekend shutdown provides opportunity for repairs, it also results in excessive refractory consumption. This is true for both AC and DC operations.

Brown Boveri Corporation

The BBC furnace design, operating at Nucor Steel Corporation, employs steel pins embedded in the furnace hearth to maintain contact between the charge and the bottom electrode. The hearth is constructed of standard high temperature insulating bricks with 80 steel contact pins, each pin having its own thermocouple and forced air cooling. The service life of this hearth has been about 250-350 heats (9,090 tonnes). As seen in Figure 4.2, there are two horizontal plates with air guide vanes in-between. The contact pins attached to the bottom plate extend through the cooling cavity between the plates, up through the hearth lining to the molten steel bath. The temperature of each pin is monitored so that the useful life of the bottom contact can be determined accurately. Uneven heating or an abnormal temperature rise usually indicates slag coverage of some of the pins.

Figure 4.2

Schematic Drawing of Brown Boveri Corporation's Air-Cooled Bottom Contact at Nucor Steel.



The replacement procedure for the bottom contact has been changed recently. Initially, a small liquid heel was allowed to solidify with a lifting hook embedded in it. This center contact section was then removed with a hydraulic pulling device. With the new procedure it is possible to hydraulically remove the contact hearth from the bottom while the furnace is hot. It is then replaced with a preassembled plug with the refractory already in place around the pins. This has reduced the furnace turn-around time for contact replacement to about one shift (8 hours).

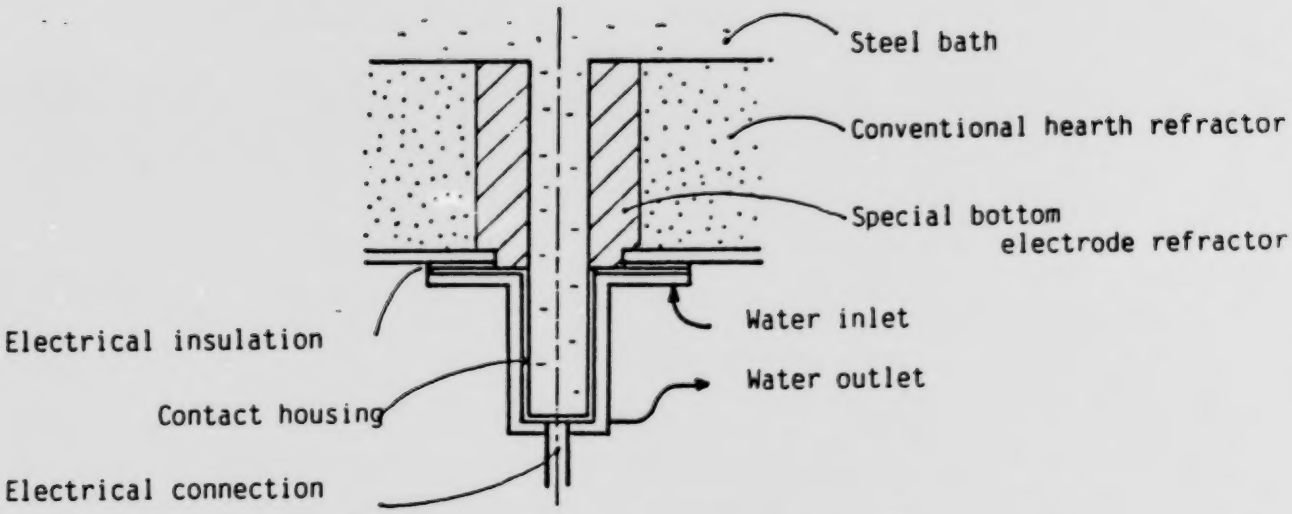
Clecim

Clecim has been associated with France's Steel Industry Research Institute (IRSID) since 1979. Clecim has licensed and is marketing IRSID's DC arc furnace technology. The technology marketed by Clecim is based upon a multi-electrode hearth. The furnace bottom, Figure 4.3, contains three water cooled steel billet electrodes, each with its own water cooling circuit. These bottom electrodes can be installed from outside the furnace. The claimed advantage of multiple electrodes is the potential for scale up and has led to a high-power DC furnace. By employing three electrodes rather than the usual single dc electrode, one can theoretically scale up without requiring enormous graphite electrode diameters. It was reported that a current density of 120KA (40KA/electrode) is well beyond that achievable with a single electrode system. It is also claimed that three electrodes will optimize energy distribution inside the furnace. The use of three electrodes, however, will decrease the savings in electrode consumption of the single electrode system and require three electrode arms and holders with associated increased costs. North American furnace operators will require proof of the safety of installing water cooling beneath the furnace hearth before considering this design. Thus far the life of the bottom billet contacts is about 150 heats. The operating experience with this design has been reported to be free of serious problems.

5. ECONOMICS OF RETROFITTING AC FURNACES

The electric furnace sector of the steel industry has introduced a number of technologies aimed at increasing the productivity and reducing the operating costs of their facilities. The drive to increase productivity by shortening the melting times[37] was achieved by increasing transformer power, rapid movement of roof lifting and swinging mechanisms, rapid furnace tilting, oxy-fuel burners, foamy slag technology etc. Concurrent with the improvement in productivity was the associated reduction in electrode and power consumption. A recent trend that will continue to improve productivity and lower electrode consumption has been the use of ladle furnaces either converted from surplus arc furnace equipment or built as new facilities. This trend has resulted in electrode consumption of about 3.5 kg/tonne (7 lbs./ton) of steel (potentially less).

Figure 4.3 IRSID - Clecim's Bottom Electrode Design



The conversion of an AC furnace to a DC furnace has as its main incentive the reduction in electrode cost. If it is assumed that DC furnace electrode consumption is 40% of that of an AC unit. The electrode cost saving or payback of the conversion obviously depends on the 'reference' condition of the AC electric furnace shop which may be considered for conversion to DC.

There has recently been a downward trend in the price of electrodes. The cost of electrodes is directly related to the price of oil. The lower the cost of a pound of electrode, the longer the payback for conversion to a DC furnace and much of the incentive for DC furnaces is lost.

Table 5.1 examines a few electric furnace "reference" operations from the point of view of electrode savings.

TABLE 5.1

COMPARISON OF APPROXIMATE ELECTRODE SAVINGS RESULTING FROM THE CONVERSION OF AC TO DC OPERATION

AC Furnace Reference Conditions	Tap to Tap Time	AC Electrode Consumption kg/tonne (lb/ton)	Electrode Savings With DC kg/tonne (lb/ton)	$/tonne ($/ton)*
1. Standard Ultra High Power (UHP) AC Furnace	120	5 (10.0)	3.0 (6.0)	10.56 (9.60)
2. Modern UHP AC Furnace with Burners, Foamy Slag, etc.	75	4 (8.0)	2.4 (4.8)	8.45 (7.68)
3. (Same as #2 but with Ladle Metallurgy Station Refining etc.	60	3.5 (7.0)	2.1 (4.2)	7.39 (6.72)
4. Same as #2 With Water Cooled Non-consumable Electrodes	75	3.0 (6.0)	1.4 (2.8)**	4.93 (4.48)

(MT19)

* $1.60 Canadian/lb. of electrode carbon.

** Estimated savings of less than 50% as erosion of electrode surfaces is not a factor in this case.

It may be seen from the foregoing table that costs savings can range from approximately $10.56/tonne of steel down to $4.93/tonne. Under normal operations, case #2, in the table, a saving of $8.45/tonne may be the most typical comparison for Ontario electric furnace operations. If, however, the cost of electrodes is falling, as quoted by the U.S. operators, to a level of $0.85 U.S. or $1.05 Cdn then the savings in case #2 will be about $6.22/tonne of steel.

The investment required for the conversion of an AC to DC furnace is fully site specific. The staff of the American DC operations visited, would not reveal the actual investments involved in their conversion other than to say that the payback is roughly 2-3 years. This would suggest an investment, based on case #1, and current electrode cost of $1.26 U.S./lb. (6.0 lb./Ton X 1.26 U.S./lb. = $7.50 U.S. ton of Steel), or $1.9 - 2.9 million CAN ($1.5 - $2.25 million US) for 100,000 ton/year furnace. Overall savings reported, however, have been anywhere from $5.00 to $8.00 US/ton (see appendix trip reports), thus making investment predictions somewhat cloudy.

In general, it must be said that each plant considering conversion to DC must assess their individual situation, i.e. the expected electrode savings, maximum DC furnace size consideration and the cost of electrical improvements required to correct any existing problems with AC furnace flicker on the power system.

Currently the improvement in AC furnace operations is continuing in most Ontario plants. The DC furnace will be evaluated in the normal course of a given company's investment plans.

6. POTENTIAL ONTARIO INSTALLATIONS WHICH COULD BE CONVERTED TO DC

6.1 Ferrous

The vast majority of existing AC furnaces (Table I, Appendix) in Ontario steel and foundry industries are in a power and size range that may be converted to DC. There is one modern furnace at Lasco, in Whitby, which is beyond the power and size capabilities of existing single electrode DC systems. All of the existing vacuum degassing and AC heated ladle metallurgy stations are within the power range of current commercially available DC systems, however, as far as can be determined DC designs for such systems have not been developed.

The ferrous industry is open minded; however, demonstrated dependability and savings of DC systems will be the basis of future decisions.

Appendix Table I and II provide an updated listing of the electric arc furnaces in Ontario and some of their opinions.

6.2 Non-Ferrous

The main driving force for the steel industry to adopt the DC arc furnace is the saving in electrode carbon consumption. This is not of primary concern in the non-ferrous industry, particularly in sulphide smelting, where the electrode consumption ranges from 2 - 3 lbs/ton of charge in the form of electrode paste which is about half the cost of carbon electrodes. The driving force for the non-ferrous industry to convert to DC operation has to be therefore, something other than carbon consumption. The possibility of increasing the power density and thereby productivity of the furnace, is being explored by one company on a pilot plant scale. Insufficient data are available to evaluate to what an extent this is feasible. Companies stated that they will only consider DC operation if they can be convinced that the conversion will result in a reduction of production cost without adversely affecting the reliability of their operation. Of concern to them is the integrity of the conducting hearth. They have to operate continuously 24 hours per day 365 days per year, whereas the steel melters are dealing with a batch operation, which permits frequent inspection and repair of the furnace hearth as required.

There are no obvious non-ferrous or alumina smelters which can benefit from a conversion from AC to DC. This picture may change as information from the proposed Ontario Hydro pilot plant becomes available.

7. POTENTIAL NEW APPLICATIONS FOR DC FURNACES

7.1 Ferrous

The steel companies of Ontario are among the most technically aggressive in the world. There is a high rate of technical development and assimilation of developments from others. The DC furnace will be adopted when its record of dependability and economy has been clarified. Expansions in mini steel plants are expected to continue and they will naturally consider DC furnaces. Ivaco has already considered DC heating of its new ladle metallurgy station but rejected the idea due to furnace life and safety reasons.

The major integrated companies have not employed electric furnaces for steel making in Ontario. This may change in the future as they seek alternative ways of producing steel without the use of coke ovens. There are many alternative routes that are to be considered but the electric furnace is an existing economic and convenient method that fits into the infrastructure of present plants. The DC system, if fully developed, may be particularly useful because of its lower power line effects in the cities where these steel plants are located.

The use of DC furnaces with hollow electrodes may have potential value in steel plants and foundries where introduction of fine particles into the melt

may be desirable. The introduction of waste dusts from baghouses into the steel bath is a possible solution to an existing costly disposal problem. The same is true for fine metallic or reagent additions into melts in both steel and foundry furnaces.

7.2 Non-Ferrous

There has been little activity in applications of DC smelting furnaces to the non-ferrous or ceramic industries. Middleburg Steel is operating a DC furnace in South Africa for the production of high carbon ferrochrome. Inco has carried out smelting tests on various materials in a 100 kW and a 1,200 kW pilot plant furnace. A DC arc furnace is reported to have started smelting spent automotive catalyst in Germany.

8.0 SUGGESTED AREAS FOR PILOT PLANT INVESTIGATIONS

There are a number of potential DC applications in the non-ferrous industry. Pilot plant tests are required in most cases to prove out the concepts and to provide technological information for scale up.

The following areas merit investigation:

Treatment of Fines,
Slag Cleaning.

Treatment of Fines

Chromite fines have been smelted successfully in South Africa to produce ferrochrome. Inco has run smelting tests with a number of fine materials. The apparent advantage of DC over AC in the smelting of fines is that the direct current drives the fine particles into the melt where they are incorporated in the melt. This results in little dust carry out from the furnace. This is not the case in AC smelting operations where dust losses are generally considerably higher.

An important advantage of this DC furnace is that it can operate directly with ore fines, without prior briquetting or pelletizing. The fines or larger fractions, up to 25 mm in size, can be charged into the furnace through the electrode. There are several advantages of charging through the center of the electrode. The fines are delivered to the hottest areas, the arc plasma and the anode spot in the melt. This provides efficient coupling between the arc power and the process.

The arc repulses the slag layer providing an open path for the fines to enter the bath with the result that only a small quantity of fines is lost to the slag or atmosphere.

The continuous flow of charge materials cools and therefore deionizes the arc. This results in increased arc resistance which means that the furnace can operate with higher arc voltages and lower currents thereby contributing to a lower electrode consumption.

The feed rate can be matched to the input power such that the charge is reduced as it is being fed. This results in no accumulation of unreacted charge material in the furnace.

It is believed that DC furnaces have an application for treating fines. Development work is required in this area.

Slag Cleaning

A D.C. furnace may also have an application for cleaning of copper and nickel slags. At this point, it is assumed that injection of carbon into the melt is more effective when using DC rather than AC and that also the electric potential will assist in the agglomeration and settling of metal and sulphide prills from the slag. Approximately half of the pay metal losses in a non ferrous smelter are in the form of prills.

9.0 SUMMARY AND CONCLUSIONS

1. The electrode consumption of a single electrode DC furnace operation is about 50% to 60% lower than that experienced in an equally powered three electrode AC furnace.

2. The average mean noise level of a DC furnace is lower than that of an AC furnace. The peak noise values are about the same.

3. The power line disturbances (flicker) of a DC furnace are about one half those of an AC furnace.

4. The maximum size and power of a single electrode furnace is limited by the maximum size of graphite electrodes produced commercially. Currently the maximum electrode size is 700 mm, thus limiting a DC furnace to 60 MW of power and 80 tonne (88 ton) in capacity.

5. The maximum size of a multi-electrode DC furnace is approximately the same as an AC furnace. The electrode savings with DC, however, will be somewhat decreased when employing multiple electrodes.

6. The incentive to convert an AC furnace to DC is essentially found in the electrode cost savings. The cost and pay back of such a conversion is site specific. The pay back appears to be about 2-4 years at current electrode prices.

7. The incentive to convert to DC may decrease to some degree, as it is suggested that the cost of graphite electrodes have been decreasing. The cost of graphite is directly dependent on the world price of oil.

8. Other methods of reducing AC furnace electrode consumption, such as permanent water cooled electrodes, may offer lower cost alternatives to DC furnaces. This may slow the move to DC technology.

9. DC furnace technology has found limited application in the non-ferrous industry to date, primarily as a result of limited interest and lack of sponsors.

10. Opportunities for employing DC furnace technology to the non-ferrous and ceramic industry may be found in the direct treatment of fines and in slag cleaning in the copper and nickel industry. However, pilot plant tests are required to prove out the concepts and to provide technological information for scale up.

11. The metallurgical industry appears receptive to DC furnace technology, however, acceptance will depend on industry confidence in the safety and dependability of the technology. The key factor in building this confidence is the development of a demonstrated dependable bottom electrode system for the DC furnace.

DC ARC FURNACE STUDY

PART B

ELECTRICAL POWER SUPPLY CONSIDERATIONS

1.0 INTRODUCTION

The Electric Arc Furnace (EAF) is a very large consumer of electrical energy with specific powers in excess of 700 kVA/ton. Because of this large energy requirement, as well as the inherent tendency of the load to fluctuate, the efficiency and stability of the EAF are matters of considerable interest to utilities and furnace operators alike.

In the EAF, heat is generated by the passage of current between one or more electrodes and the furnace charge. As the current passes through the gap between the electrode and the charge, it forms an arc which generates the heat required to melt the charge. A transformer, usually fed directly from the electrical distribution supply, is used to provide the relatively low voltages (<800 volts) and very large currents (upwards of 30000 amperes, typically) that are required by the arc. The distance between the electrode and the charge determines the length of the arc which in turn, for a given supply voltage, results in a certain arc current and power into the furnace. Consequently, arc furnaces are equipped with a means of controlling the electrode position, and hence heating level. As will be seen, some furnaces are also equipped with a means of controlling the arc current directly, which allows more flexibility in controlling the operating point.

Until recently, EAFs have used three phase alternating current (AC) exclusively. Now, with the development of high-current moderate-cost power semiconductors, it is practical for furnaces to use direct current (DC), for both new installations as well as the retrofitting of existing furnaces.

The purpose of this portion of the state-of-the-art study of EAFs utilizing DC current is to investigate the AC to DC conversion systems and the potential problems and advantages of using DC for both the user and the supplier of the electrical energy.

2.0 AC to DC CONVERSION

Although there are several ways in which incoming AC power can be converted to DC for use in an arc furnace, the full bridge static converter type works well and is currently the only one used for either new or retrofit installations.

Full bridge static converters employ either diodes or thyristors. The diode bridge approach, shown in Figure 1, is generally the lower cost of the two,

while the thyristor-type static converter (Figure 2) offers some significant technical advantages. These include the independent control of arc parameters and the reduction of current surges (and their effect on the electrical supply network). As a result of these advantages, suppliers of the static converters have almost exclusively chosen thyristor-type converters.

When using a diode-type converter the selection of an operating point requires both the selection of an appropriate tap on the furnace transformer and control of the arc using conventional electrode arm control adapted for DC. Since the diode-type converter has no direct control of the arc current, the operating voltage/current ratio chosen must be a stable operating point on the load characteristic of the furnace.

With the diode-type converters, the short-circuit current is limited by the impedance of the transformer and any additional limiting reactance /21/. For furnaces converted from AC to DC operation using the existing furnace transformer, some additional reactance may have to be added in the AC circuit to limit the short circuit current. This is due to the reduced reactance of the secondary buswork in DC operation. The components of the converter employing diode rectifiers for both new and retrofit installations have to be dimensioned to handle the higher current level during the frequent short circuits which occur during normal operation of the furnace, especially during the bore-in and early melt-down phases.

Thyristor-type rectifiers, by contrast, allow dynamic control of the current intensity by enabling the control of the firing angle of the thyristors. This allows independent adjustment of the arc current (by firing angle control) and voltage (by conventional electrode position control) to stabilize the selected operating point and to limit the short circuit current, reducing or eliminating the need for current-limiting reactors on the AC side.

To limit the dynamic short circuit current, ie the increase in arc current which occurs before the control circuitry of the thyristor-type converter can compensate, a reactor coil must be installed on the DC side. In addition to limiting the initial current peaks for the protection of the thyristors, the reactor coil also stabilizes the arc by smoothing the current fluctuations normally associated with movements of the furnace charge. Without the reactor, the thyristor-type converter would have to be sized to handle the resulting large surge currents.

Whether a diode-type or thyristor-type converter is used, certain equipment is required which is common to each. First, some type of cooling for the semiconductors must be provided to dissipate the power losses in the rectifying devices. In all but very small research furnaces this normally involves water cooling.

Secondly, where groups of rectifying devices are used in parallel for increased current capacity (as is normally the case with presently available devices), some method must be provided for balancing the current through the parallel devices. In addition to this, each of the semiconductor devices should be fused to protect the semiconductor in the event of any faults which may cause excessive currents in individual devices.

For economic reasons, when AC arc furnaces are converted to DC operation the furnace transformer is not normally changed/1,16/. This prevents the supplier of the converter from using certain specialized converter circuits for optimizing performance characteristics. Examples of such circuits include a six-pulse-half-wave converter for reducing semiconductor losses /10/, and a twelve-pulse-full-wave converter for reducing harmonic loading of the main electrical supply and eliminating the possible need for harmonic absorption circuits /36/.

3.0 POWER SEMICONDUCTORS

Many types of power-switching semiconductor devices are currently available, including transistors, diodes and thyristors. This section will concentrate on thyristors, however, since arc furnace static converters now use these devices exclusively.

3.1 Thyristor characteristics

For historical reasons the thyristor family, which is composed of several different devices, is often referred to as "SCRs" (Silicon Controlled Rectifiers) whereas in reality SCRs are only one member of the thyristor family. The thyristor family also includes such devices as DIACs, Silicon Controlled Switches (SCS) and Gate Turn Off (GTO) thyristors.

Without going into a detailed description of the operation of a thyristor (this information is available in many reference books such as reference/60/), the important characteristic of the thyristor as applied to power static converters is its ability to block forward conduction until the device is triggered and then carry large amounts of forward current with a low forward voltage drop. (Minimizing the forward voltage drop is desirable so as to limit the internal power dissipation which must be removed by the cooling system.) Once the thyristor has been triggered and is conducting current in the forward direction, it will continue to conduct current, even if the trigger signal is removed, until the forward current drops below some relatively small holding current. In the reverse direction the thyristor has a low leakage current for voltages up to a certain rated value.

The forward triggering characteristic of the thyristor allows control over when the converter input voltage is connected to the output, in contrast to a

diode-type converter where the input voltage is unconditionally connected to the output whenever the input voltage exceeds the output voltage. Using this characteristic of the thyristor it is possible, by monitoring the output voltage and/or current, to adjust the trigger time of the thyristor to regulate either the output voltage or output current. From the literature surveyed it appears that the most common arrangement is to use the thyristor trigger time control to regulate the arc current, with the arc voltage adjusted by varying the electrode position.

3.2 Thyristor Failure Mechanisms

The two primary failure modes for thyristors are: reverse voltage breakdown and surge failure /61,62/. Because of the relatively low operating voltages of the DC arc furnaces (<800 volts), reverse breakdown can be avoided by proper design and is not normally a problem.

Surge failure occurs when, during a current surge, the heat generated within the device exceeds the ability of the cooling system to remove it. This leads to destruction of the device by the localized increase of both temperature and current density, as well as by mechanical damage caused by thermal shock. A series current-limiting fuse is normally used to protect the thyristor from damage of this type.

The prevention of thyristor failures appears to be well understood as both the literature survey and discussions with the users and suppliers of the thyristor-type converters indicate that thyristor reliability has not been a problem in its application to power converters for DC arc furnaces.

4.0 FLICKER

The demand for electricity by an electric arc furnace is characterized by large random fluctuations in current due to intermittent short and open circuits, especially during the bore-in and early melting phases. This change in current flow results in a variation in the voltage drop across the power system network impedance which manifests itself as a change in the voltage at the user's point of connection to the network. While this voltage fluctuation is not a direct problem to the utility's supply network, it affects the quality of power for other customers connected to the same point in the network.

The magnitude of the voltage fluctuations depends on the pertinent parameters of the supply network. For AC furnaces, fluctuations have been observed in the range of 0.06 to 0.093 %/MVA of installed furnace capacity, based on a network short circuit power capacity of 1 GVA./23/

Voltage fluctuations result in fluctuations of the luminous flux from incandescent lights which, if in the proper frequency range, is noticeable by

the human eye. This disturbing effect is known as "flicker". Studies have indicated that in the range of 6 to 10 Hz, variations in supply voltage as low as 0.5 % are noticeable/62/. Because of the frequency dependence aspect, it is difficult to relate this finding to the measurements cited above. However, it turns out that in most applications the flicker voltage is enough of a problem to warrant attention. In addition to the flicker problem, variation in the supply voltage could cause oscillations in the torque of asynchronous machines and possibly problems with sensitive electronic equipment./67/

For the foregoing reasons, it is best if the arc furnace is supplied from a point in the power system network where the short circuit current capacity is sufficiently high to limit the terminal voltage fluctuations to an acceptable level. However, if this is not possible then it may be necessary to reduce the voltage fluctuations by installing reactive power compensation equipment such as a static var compensator or a synchronous condenser. With reactive power compensation in place, the load phase angle is nearly 90 degrees away from the (inductive) power system impedance, which therefore minimizes the effects of load variations on terminal voltage /62,13/.

4.1 Flicker and the DC Arc Furnace

If it is assumed that the DC arc furnace is operated at a constant current and that there is sufficient reactance on the DC side to limit the dynamic current surges and stabilize the arc, then the short circuit current will be limited to essentially the normal operating current. By contrast, the AC furnace short circuit current cannot normally be limited to much less than twice the normal operating current/13/. Figure 3 shows the current loci for a DC and an AC furnace, indicating the comparative fluctuations in reactive current. The result of this is that the expected variation in reactive current and consequently the amount of flicker from a DC arc furnace, using a thyristor-type converter and operating with constant current, should be approximately half that of an equivalent AC furnace, or even less. The literature indicates that measurements of existing DC installations have shown a reduction in the flicker to between one third and one half of that for an equivalent size AC furnace/13/. This is approximately the same improvement which is gained by the addition of reactive power compensating equipment to an AC furnace/13/.

As a result of the reduced effect on the mains voltage, a DC furnace could prove especially attractive where the power supply network is not very stiff (ie. has a low short circuit capacity relative to the nominal furnace operating current).

It should be noted that if a diode-type converter is used so that the furnace current cannot be kept constant, or if the current is allowed to fluctuate for other reasons, the same improvement in flicker effect cannot be expected. However, the more stable arc operation of the DC furnace will still offer some

improvement over AC operation.

5.0 HARMONICS

The nonlinear characteristic of the arc in an AC arc furnace leads to non-sinusoidal distortion of the current which can be described by harmonics. The number of harmonics of significant magnitude is considerable in an AC furnace. In a DC arc furnace with its constant current and stable arc, the harmonics due to the arc itself are negligible/36/. However, the static converter supplying the DC arc furnace generates harmonics.

It can be shown/63/ that the static converter generates harmonics at

$$pk +/-1$$

where p is the pulse number of the converter (typically 6 or 12)
k is an integer 1,2,3...

The theoretical amplitude of these harmonics will be

$$I_h = \frac{1}{h} * I_1$$

where I_h is harmonic current
h is harmonic number
I_1 is fundamental current

Since most retrofit installations will be 6-pulse rectifiers because of the transformer configuration, the theoretical harmonics and amplitudes for retrofit installations (or new installations using 6-pulse converters) would be as shown in Figure 4.

In reality, however, the amplitudes of the harmonics are typically considerably different from the theoretical. The high order harmonics are generally reduced by intrinsic circuit reactances, although if there is insufficient reactance on the DC side to smooth the DC current, it can happen that the amplitude of the 5th harmonic may in fact be larger than the theoretical value/63/. Typical values of harmonic current for a six pulse converter are included Figure 4 for purposes of comparison/66/. Harmonic current data provided by one supplier for a system with no harmonic filtering agrees very well with the typical values shown in Figure 4 for a six-pulse converter.

From the general equation for the expected harmonics it can be seen that by using a 12-pulse converter, the 5th, 7th, 17th, 19th,... harmonics would be eliminated and the total harmonic loading on the supply network would be significantly reduced.

According to the literature/36/, detailed measurements of a DC furnace during the melt-down phase have indicated that those frequency portions which are not specifically related to the converter are so small that their contribution to the distortion factor can be neglected. Consequently since the order of the harmonics is well known, compensation to eliminate the harmonics using series inductors and capacitors tuned to the harmonic frequency is quite simple/66/.

6.0 POWER CONSUMPTION

Since in the DC furnace the 3 phases of the AC supply jointly feed the single arc, the result is a balanced load on the power system. Controlled tests of two retrofit installations to compare the electrical energy consumption of a DC vs. an AC furnace under comparable operating conditions indicate an overall electrical energy requirement for the DC furnace of 1.8 % to 3.3% less than that of the corresponding AC furnace/1,16/.

The improved energy efficiency is attributed to improved energy transfer of the DC arc and the elimination of inductive losses in the secondary buswork/44/. These improvements more than offset the losses in the static converter (thyristor losses and grading circuit losses).

6.1 Electrode Current

Due to the uniform current distribution in an electrode carrying DC current as compared to the skin effect present with AC current, an electrode can carry approximately 30 percent more DC current than AC current, for the same stress./11/

7.0 POWER FACTOR

There appears to be very little information available in the literature on the uncompensated operating power factor of an AC versus a DC furnace, although in general the DC arc furnace power factor will tend to be somewhat better (ie closer to unity) because of the lower reactance of the furnace. However, since both types require reactive power and most utilities invoke a penalty for reactive power demands, it is usually advantageous in either case for the arc furnace installation to include some reactive power compensation equipment to reduce the average reactive power requirement and thereby improve the normal operating power factor.

For the AC furnace this average reactive power compensation is frequently done using either static var compensators or synchronous condensers /64,65/ because this also serves to compensate the flicker problem. For the DC furnace, on the other hand, the compensation is frequently done using harmonic filters since these may be required anyway, to limit the harmonic loading of the mains

supply.

The literature tends to indicate that because of the more stable operation of the DC arc furnace, as well as the balanced loading on all phases and the reduced reactive current fluctuation, the cost and complexity of the power factor compensation is less for a DC furnace than for an AC furnace.

8.0 CONTROL

For the AC arc furnace, the arc voltage and possibly the arc current for each phase is measured and used to control the electrode position to maintain the arc voltage or impedance at the set point. The control principle for the AC furnace is shown in Figure 5. When the furnace is operating, it is impossible to keep the length of the arc constant because of the movement of the arc and melting of the charge as well as the speed of the electrode arm positioning equipment trying to compensate for these changes. These changes in arc length result in changes in the arc voltage and more importantly in the arc current with its resulting effects on the supply network (ie flicker).

When considering a DC furnace with a thyristor-type converter there are two control mechanisms. The first is the thyristor firing angle controlling the output of the converter and the second is the electrode position control. A representative control circuit is shown in Figure 6. In this controller the output DC current is monitored and the firing angle of the thyristors in the static converter can be quickly adjusted to maintain the output current at the set point. The arc voltage is monitored and electrode position is controlled to maintain the arc voltage as close to the set point as possible.

Since maintaining a constant arc current is desirable in view of the effects of fluctuating current on the mains supply voltage, the firing angle control system will continuously adjust the firing angle of the thyristors to maintain a constant current even though the arc length is continuously changing. However, since there is a short delay between the time that the control system recognizes that change is required and the time when the change in firing angle will take effect, a reactance is placed in the DC circuit to limit the rate of rise of current. The limitation of current by the reactor and firing angle control is shown in Figure 7.

The combination of the reactor and the high speed current regulation not only limits the short circuit current to very nearly the set operating current, but also significantly reduces the length of time that current interruptions occur after a charge is added and melt-down begins. This factor causes a further reduction in the extent of current fluctuations.

While there are few details described in the literature about the design of the control systems for the existing DC furnaces, on-site discussions with op-

erating plant personnel indicate that at least the existing DC furnaces are as easy to use and as reliable as those for AC furnaces.

9.0 PROBLEMS

Very early in the development of DC furnaces there were a few minor problems reported relating to the current sharing between parallel rectifiers as well as problems relating to inadequate cooling./52/ In-plant discussions with the operators of operational DC arc furnaces revealed no problems of these types.

The only unexpected problem found during the research for this report was the heating of magnetic materials (ie steel) in the vicinity of the high current conductors leading from the secondary of the furnace transformer to the rectifier cabinet. The solution consisted of a combination of increasing the separation between the high current conductors and the surrounding steel, and replacing the steel with non-ferromagnetic material where possible. While this problem has been solved, it demonstrates that the high current cable-routing techniques needed for AC arc furnaces are equally applicable to DC arc furnaces, particularily for the cables from the furnace transformer to the rectifier.

10.0 CONCLUSIONS

The development of high-current power semiconductors, specifically thyristors, has opened the way for electric arc furnace suppliers to consider the use of DC current. While the literature tends to stress the non-electrical advantages of DC arc furnaces, particularily reduced electrode consumption and acoustical operating noise, there are also electrical advantages to be gained.

The most important of these is that, if operated correctly, the DC arc furnace can reduce the effect known as "flicker" to between one third and one half of that of an equivalent sized AC furnace. While it is true that the AC to DC converter generates harmonic currents, the magnitudes and frequencies of these harmonics are known and relatively constant, making them easy to compensate if required. Tests have indicated that a DC furnace has a slightly smaller electrical power consumption than the corresponding size of AC furnace. The extra degree of control made possible by the use of a thyristor-type converter allows better control of the power input to the furnace throughout the entire melt cycle than either a DC furnace having a diode-type converter, or an AC furnace.

While there appears to be rather little in the literature relating to the power factor of an arc furnace for the various phases of a melt for either AC or DC, the compensation used to improve the power factor (if required) tends to be lower in cost and complexity for the DC furnace than for the AC furnace.

For the above reasons it appears that from an electrical standpoint the DC arc furnace is somewhat preferable to an AC furnace. In most cases, this preference alone may be insufficient to outweigh the extra cost. However, when combined with other metallurgical advantages as discussed in PART A of this report, or in locations where a weak electrical mains supply makes flicker compensation mandatory, the economics could favour the DC arc furnace.

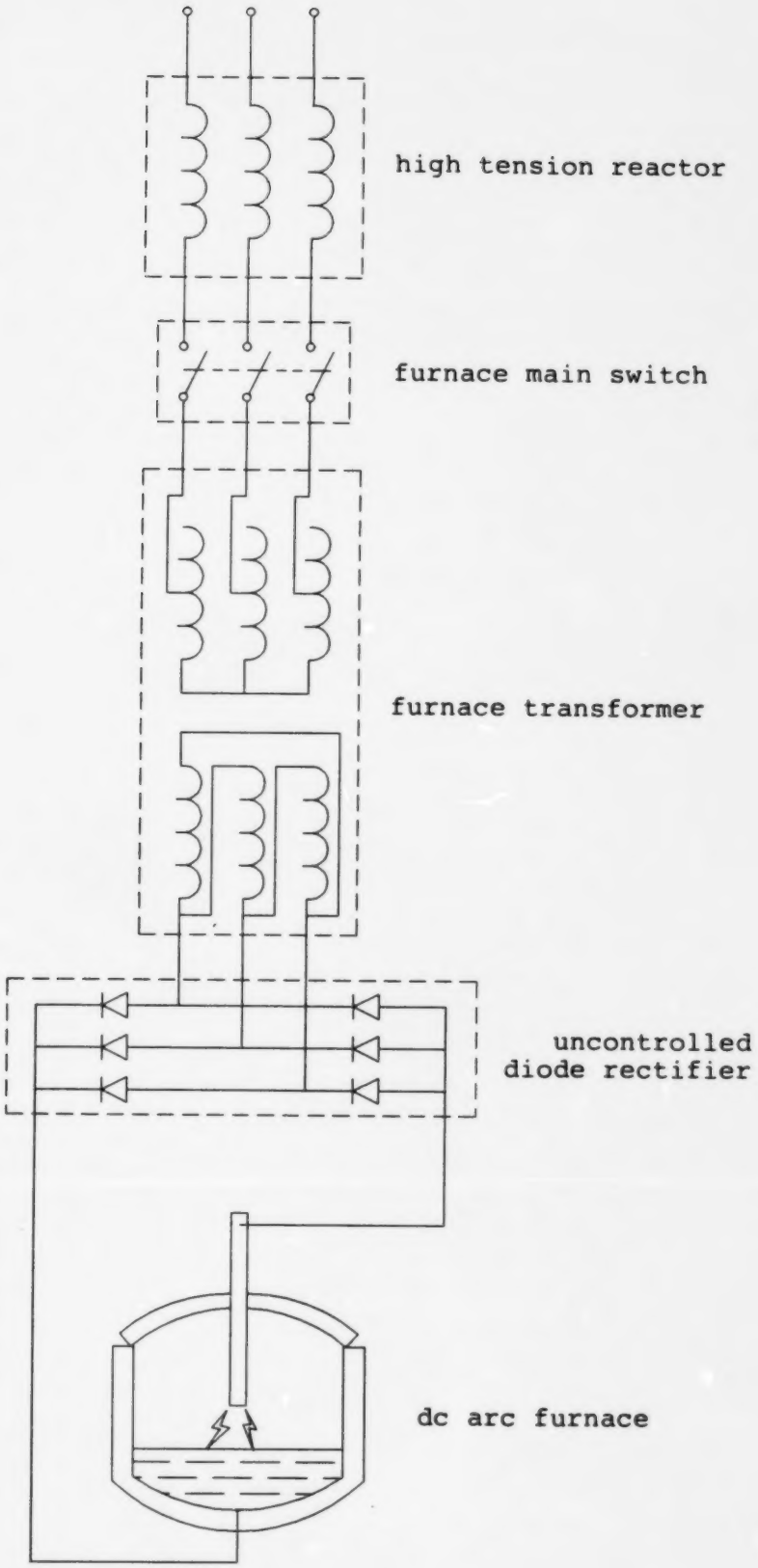


Figure 1: dc Arc Furnace Diode-Type Static Converter

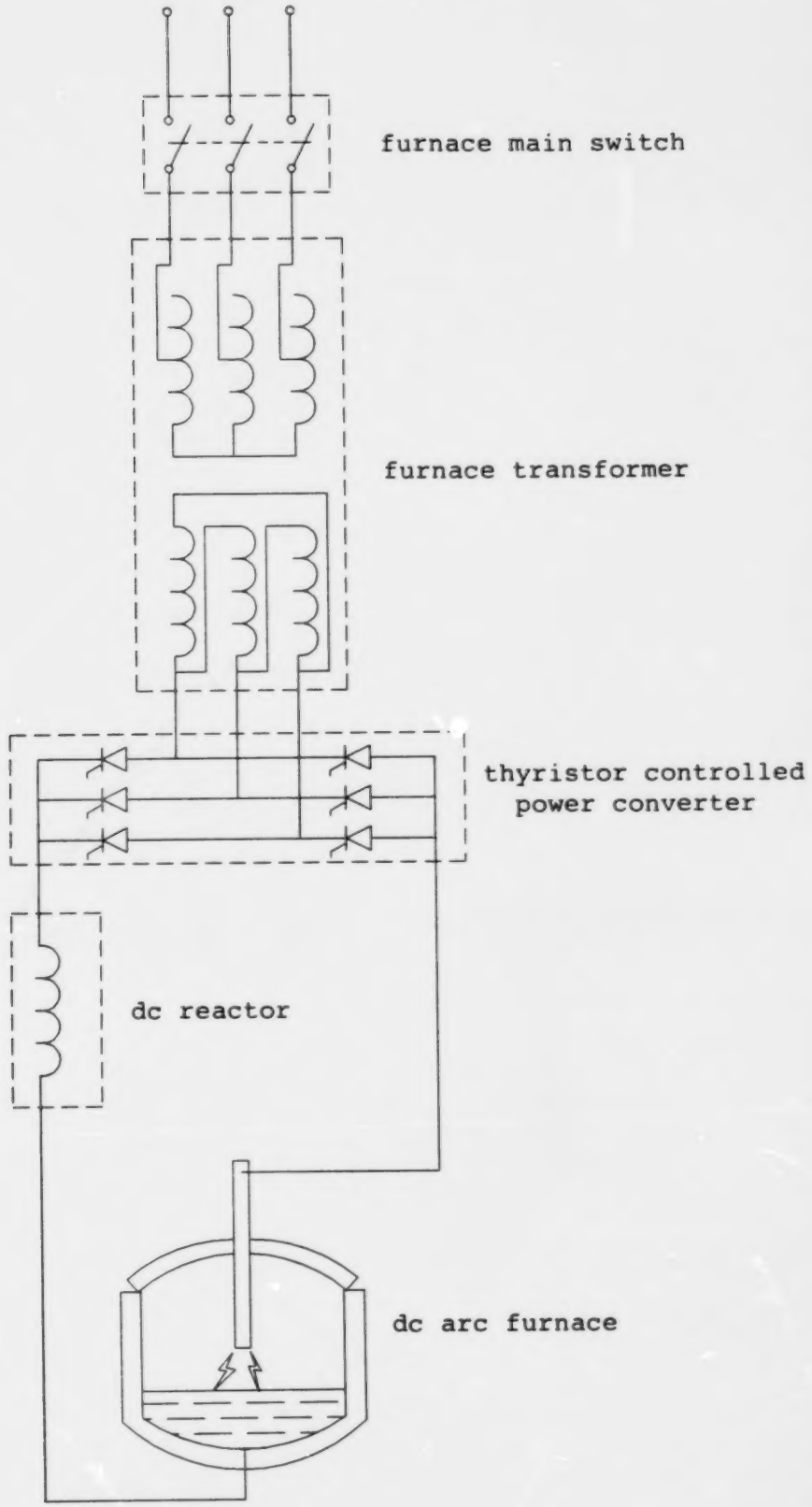


Figure 2: dc Arc Furnace Thyristor-Type State Converter

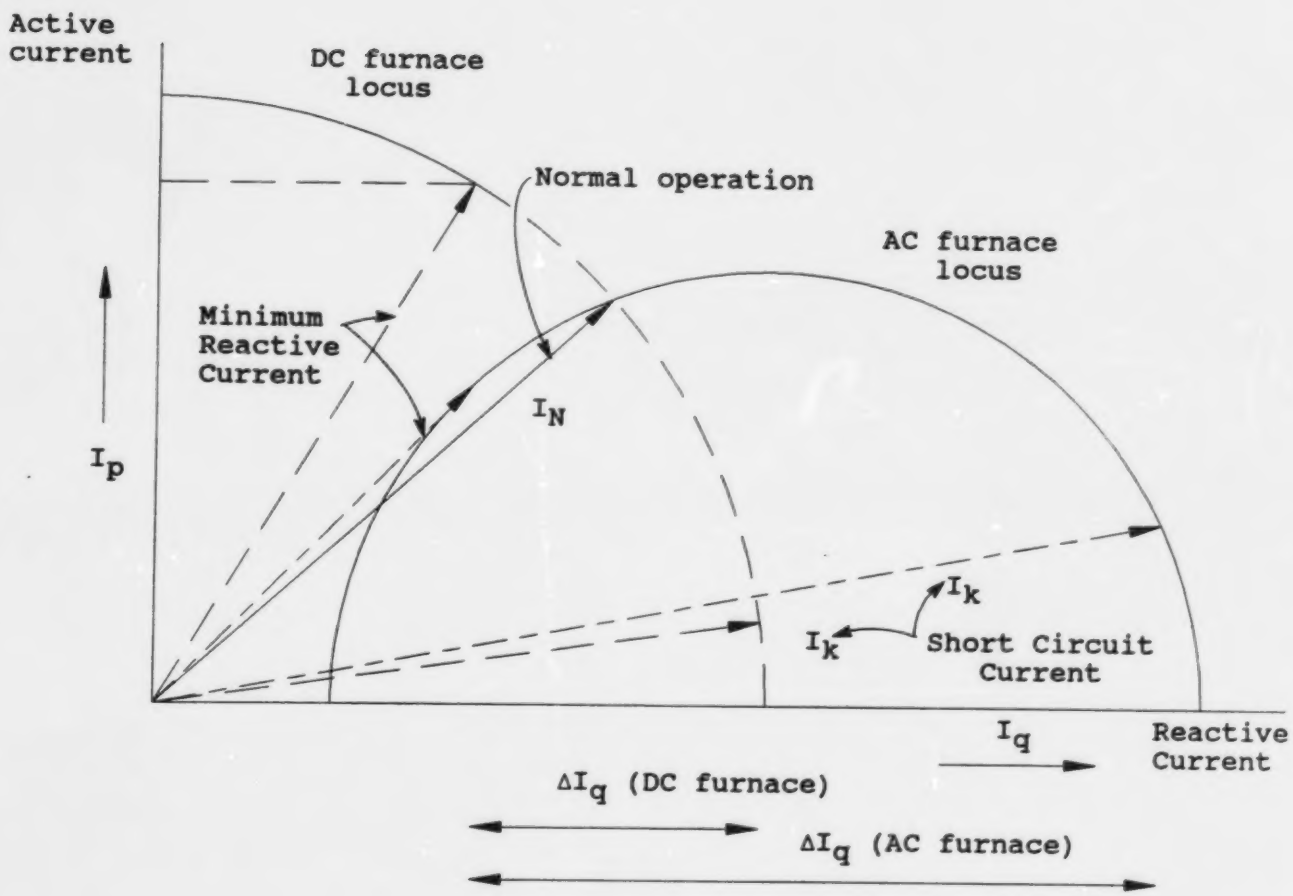


Figure 3: Current Loci of DC Arc Furnaces and Three-Phase AC Arc Furnaces

ΔI_q = maximum fluctuation of reactive current (leading to flicker)

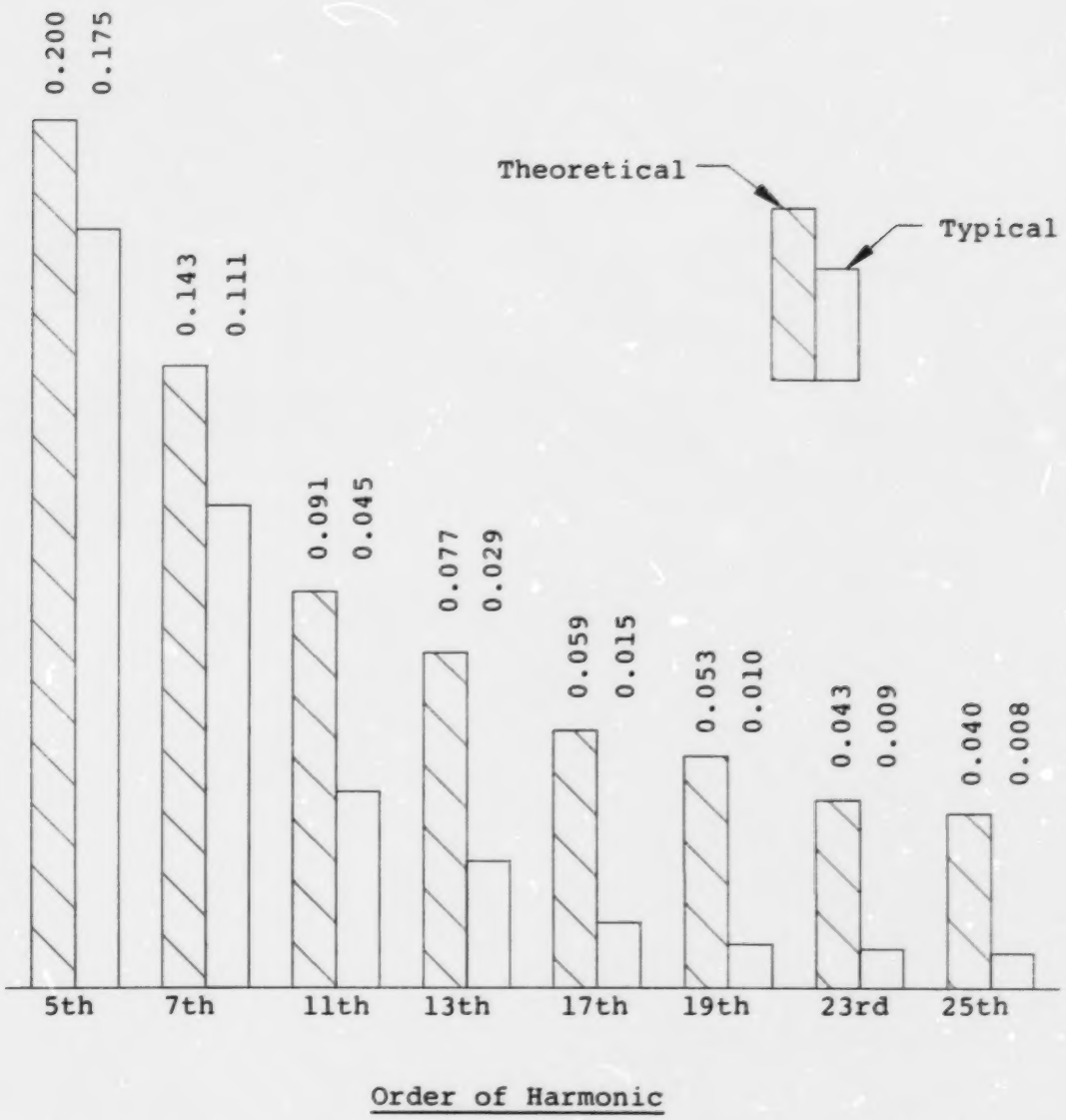
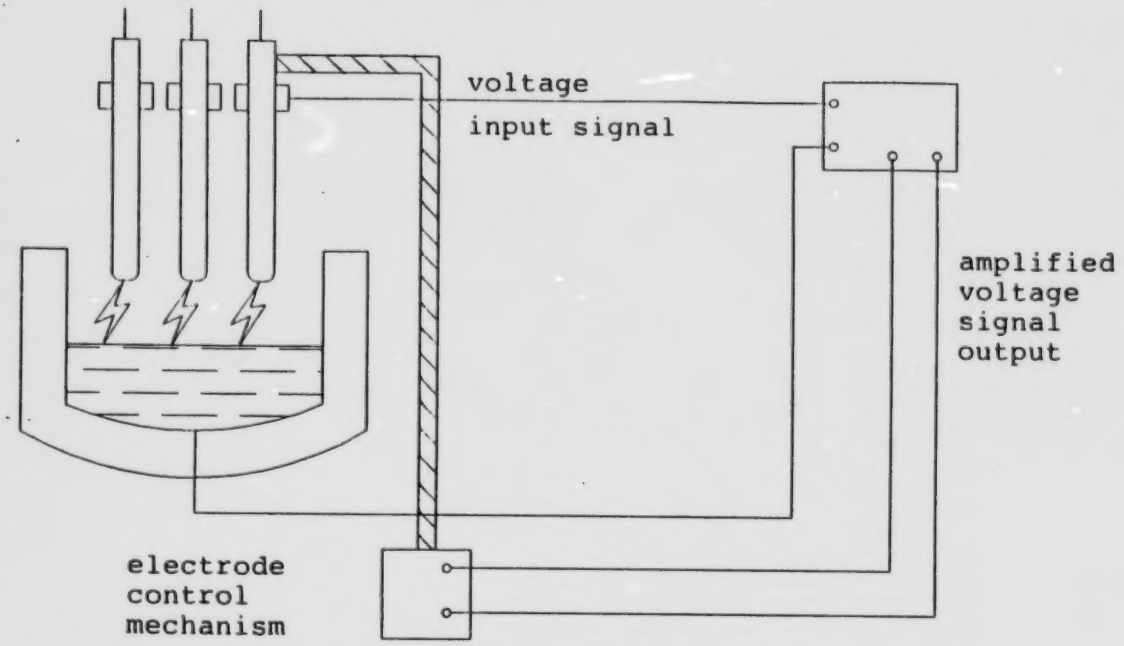
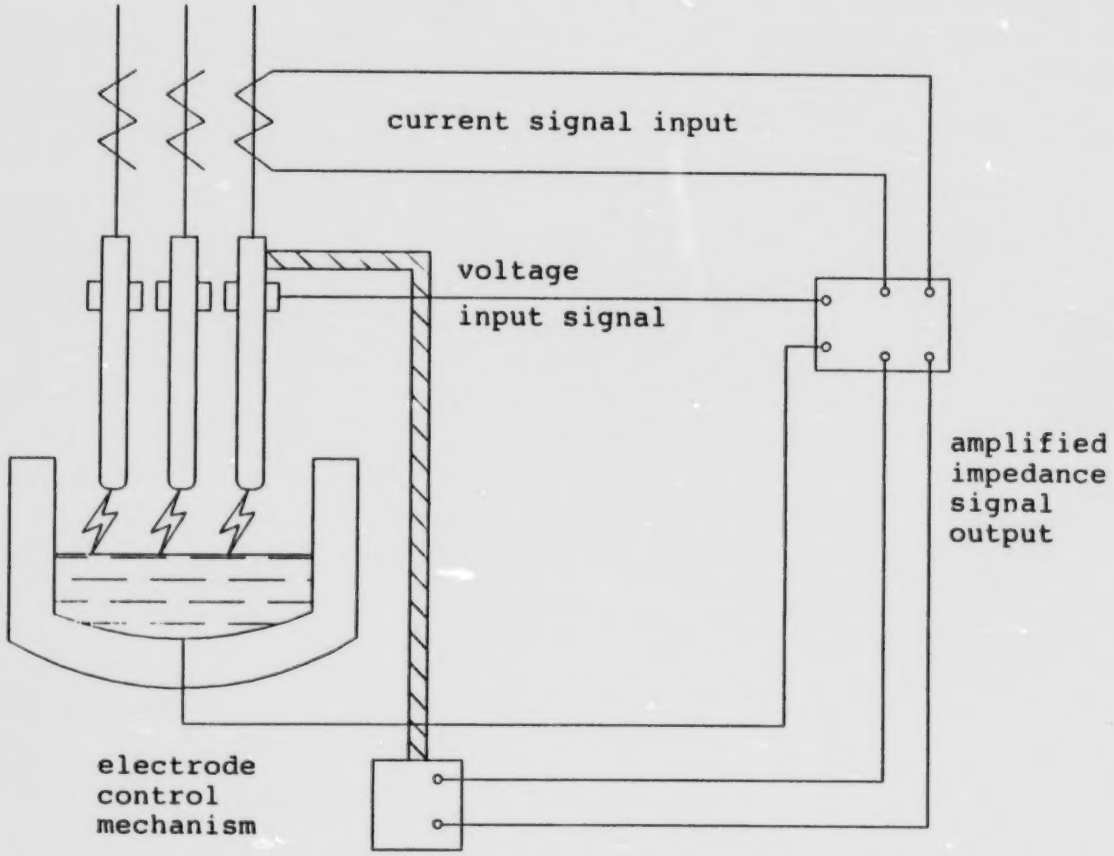


Figure 4: Theoretical and Typical Values of Harmonic Current for a Six-Pulse Converter



(a) using arc voltage as control signal



(b) using arc impedance as control signal

Figure 5: ac Arc Furnace Control

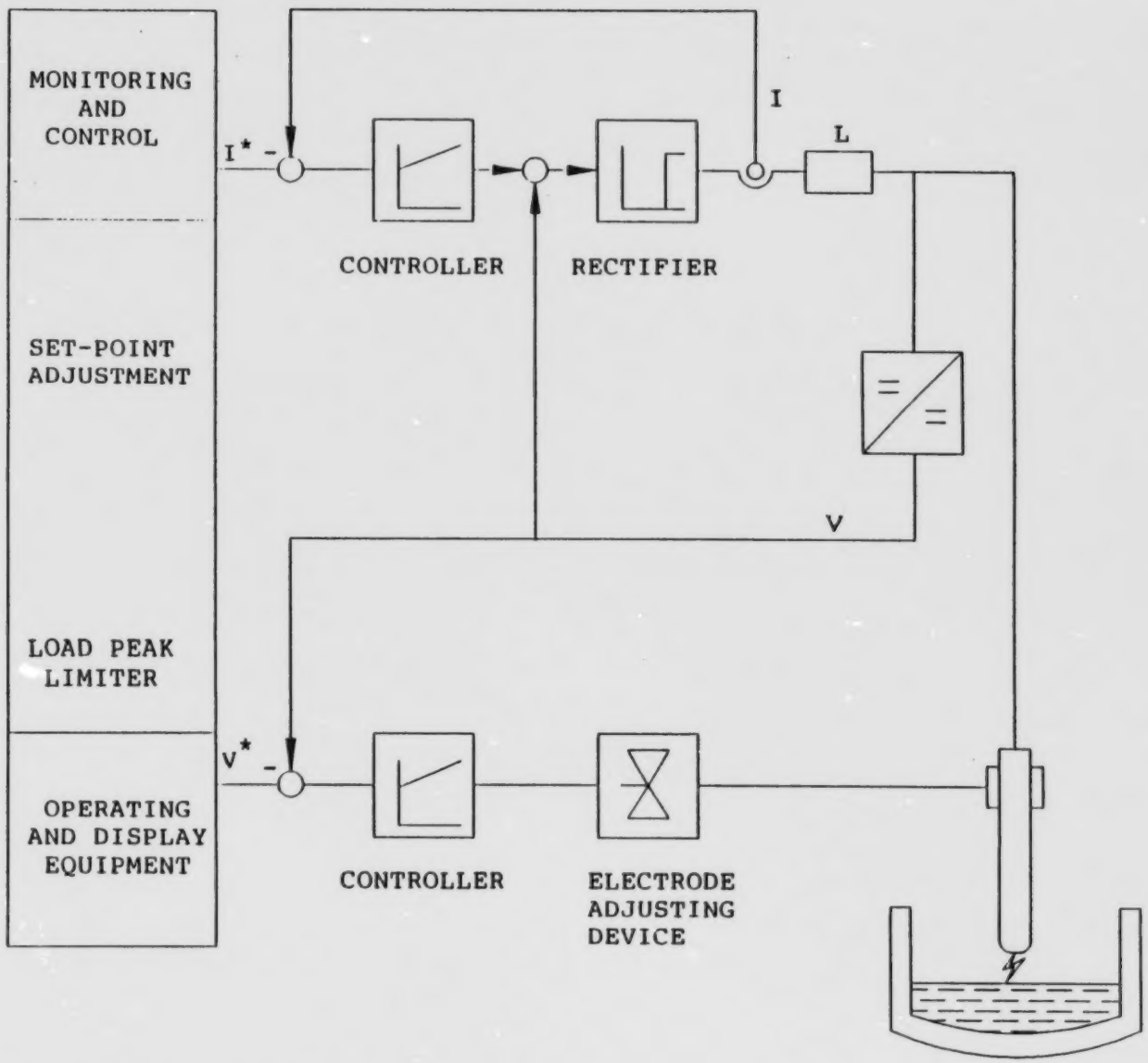


Figure 6: Control Principle of the dc Arc Furnace

I_B - Operating current
t_1 - Moment of short circuit
I_{K0} - Uninfluenced short circuit current
t_2 - Moment at which firing angle control takes effect
1 - Curve of short circuit current without reactor
2 - Curve of short circuit current with reactor
3 - Curve of short circuit current with reactor and firing angle control

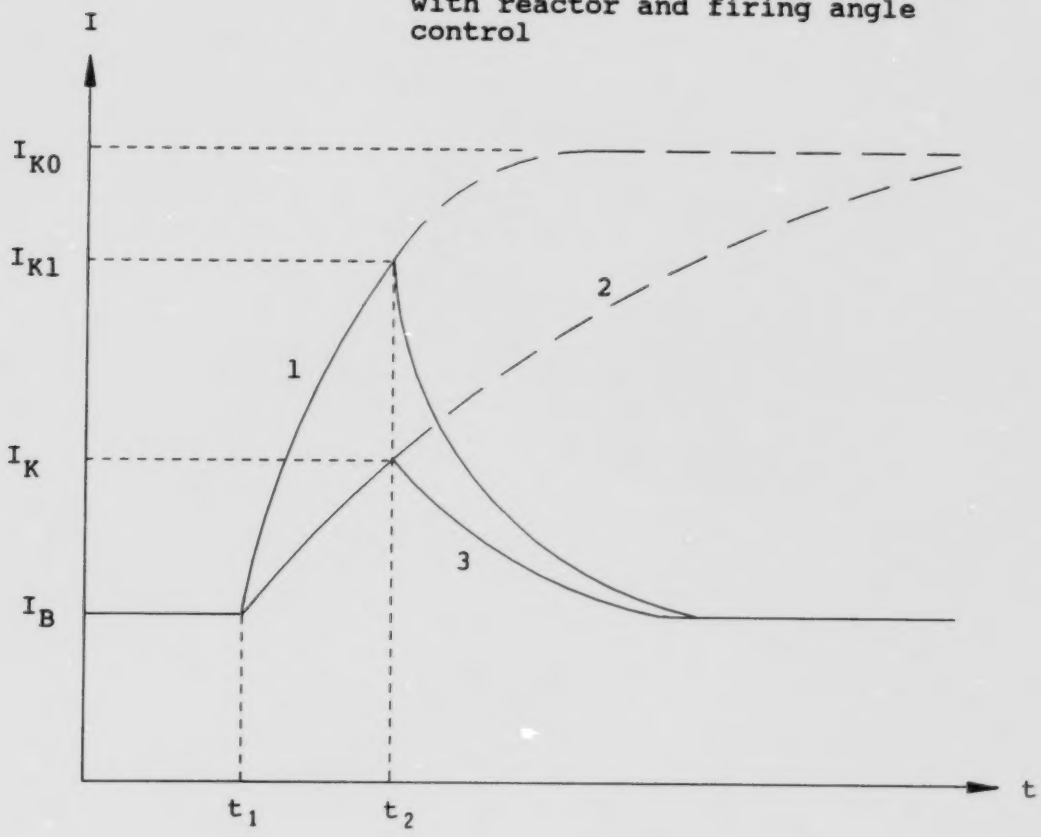


Figure 7: Limitation of Short-Circuit Current by Reactor and Firing-Angle Control

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APPENDIX - TABLE I

FERROUS ELECTRIC ARC FURNACE PLANTS IN ONTARIO

Company	Location	Product	Furnace Data	Manufacturer
Lasco	Whitby	Steel	65T, 45 MVA 18" Dia. Electrodes	Whiting
Lasco	Whitby	Steel	130 T, 95 MVA 24" Dia. Electrodes	Empco
Lasco	Whitby	Ladle Furnace	not available	Asea/Whiting
Ivaco	L'Original	Steel	65T, 27.5 MVA 18" Dia Electrodes	American Bridge
Ivaco	L'Original	Steel	65T, 27.5 MVA 18" Dia. Electrodes	American Bridge
Slater Steel	Hamilton	Steel	60T, 40 MVA 18" Dia. Electrodes	American Bridge/Whiting
Slater Steel	Hamilton	Ladle Furnace	40T, 17 MVA 16" Dia. Electrodes	Midland-Ross
Atlas Steels	Welland	Steel	70T, 30 MVA 20" Dia. Electrodes	Whiting
Atlas Steels	Welland	Steel	70T, 30 MVA 20" Dia. Electrodes	Whiting
Atlas Steels	Welland	Steel	30T, 15 MVA 16" Dia. Electrodes	Whiting
Atlas Steels	Welland	VAD/Steel	70T, 15 MVA 12" Dia. Electrodes	Whiting

Ferrous Electric Arc Furnace Plants in Ontario (Cont'd)

Company	Location	Product	Furnace Data	Manufacturer
Courtice Steel Ltd.	Cambridge	Steel	25T, 12.5 MVA 14" Dia. Electrodes	Empco
Courtice Steel Ltd.	Cambridge	Steel	40T, 33 MVA 18" Dia. Electrodes	Empco (on order)
Dofasco	Hamilton	Ladle Furnace	300T Vacuum Degassing	Daido
Stelco	Nanticoke	Ladle Furnace	3x160T, 16.5 MVA	Lectromelt
Dofasco Foundry	Hamilton	Iron/Steel	6T, 4 MVA 10" Dia. Electrodes	Whiting/Volta
Dofasco Foundry	Hamilton	Iron/Steel	6T, 7 MVA 10" Dia. Electrodes	Whiting/Volta
Algoma Steel Corp.	Sault Ste. Marie	Steel	12T, 5 MVA 12" Dia. Electrodes	Lectromelt
Esco Ltd. (Foundry)	Port Hope	Steel	6T, 3.4 MVA 8" Dia. Electrodes	Lectromelt
CAE Metal Abrasives (Foundry)	Welland	Steel Shot	8T, 5.4 MVA 10" Dia. Electrodes	Whiting
Neelon Castings Ltd. (Foundry)	Sudbury	Steel Castings	8T, 5.4 MVA 10" Dia. Electrodes	Whiting

TABLE II

NON FERROUS ELECTRIC ARC FURNACE OPERATIONS IN ONTARIO

Company	Location	Product (Operation)	FURNACE DATA						
			Type of Furnace	Capacity	MVA	Volts	KA	Electrode Diam, in.	mm
Washington Mill	Niagara Falls	Al_2O_3	3Ø	≈ 100 TPD	10	200-230	21	18	460
Electro Minerals	Niagara Falls	Al_2O_3	3Ø	≈ 150 TPD	15	200-230	26	24	610
Electro Minerals	Niagara Fals	Al_2O_3 & Various Products	3Ø		3.7	200-230		14	356
Exolon-Esk Ltd.	Thorold	Al_2O_3	3Ø	≈ 100 TPD	10	200-230	22	20	508
General Abrasives	Niagara Falls	Al_2O_3	3Ø	≈ 100 TPD	10			17	432
General Abrasives	Niagara Falls	Mag-Chrome Oxide	3Ø		3.6			12	305
Norton	Niagara Falls	Al_2O_3	3Ø		6			14	356
Norton	Niagara Falls	Al_2O_3	3Ø		4			12	305
Falconbridge Ltd.	Falconbridge	Ni-Cu Matte	2 x 6 in Line	≈ 1500 TPD	27.0	400	26	56 [1]	1,422
Kidd Creek	Timmins	Slag Cleaning	3Ø		3	100-110	18-20	24	610
Inco	Port Colborne	Experimental	DC (Electrode)	--	1.2	100-150	12	9	230
Cyanamid	Niagara Falls	CaC_2	3Ø	≈ 300 TPD	55	230	125	63 [1]	1,600
Cyanamid	Niagara Falls	$Ca(CN)_2$	3Ø	?	25	100	10	8	203

[1] Soederberg Electrode

(MT19)

APPENDIX

OTHER CONTACTS MADE

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FAX 823-1936

13. List of Ontario Steel Company Contacts
Appendix.

January 21,1988

ONTARIO STEEL PRODUCERS ATTITUDES & COMMENTS ON DC ARC FURNACES

Algoma Steel: (Mr.T.G. Burgan)	They are considering a ladle metallurgy vacuum tank station and RHOB station, although neither will consider DC heating. Companies in this field have not adopted DC power.
Atlas Steel: (Mr. R. Carson)	They hold an open mind towards DC furnaces. They have evaluated them purely on economics and dependability. They have a vacuum degassing three electrode AC furnace station (70-ton, 15 MW) which was commissioned in 1978.
Courtice Steel: (Mr.T.W.McPherson)	They also have an open mind toward DC furnace should they become dependable. They are presently considering converting an existing 25-ton furnace to an AC ladle metallurgy station.
DOFASCO: (Mr. P. Stubbs)	Dofasco has no new electrics planned and have no definite position on DC furnaces.
IVACO: (Mr.D.Goldsmith)	Ivaco has considered a DC furnace for a ladle metallurgy station but rejected it for life and safety reasons. They considered the bottom electrode life a problem but Ivaco will keep an open mind for future developments.
LASCO: (Mr. J. Gerrard)	Lasco is going to consider DC furnaces in future expansion plans. They are following the progress being made in DC furnaces. The usual economic and technical comparisons will dictate the choice.
SLATER: (Mr. B. Bowman)	Slater is concerned about the DC furnace bottom life. Slater is keeping an open mind to DC furnaces and conversions when bottom life concerns are eliminated.
STELCO: (Nr. K. Heyer)	Stelco does not have electric furnace facilities in Ontario. There are three AC ladles at Hilton Works (160 ton each). The power supply for these ladles is a 16.5 MW unit designed by Lectromelt.

January 21, 1988

PRIVATE COMMUNICATION WITH:

R. Pugh, Sr.Res.Assoc,
Stelco Inc., Edmonton

By F. Pearce

Bob Pugh is one of the most knowledgeable EAF process metallurgists in Canada.

Some points from the conversation follow:

1. AC furnaces melting rates are in the range of 80-100 minutes tap-to-tap time. Can be better but sequencing with a caster quite often sets the timing. The addition of oxyfuel burners assists in improving productivity.

2. The high speed furnace with non-consumable electrodes will result in 5 to 6 lbs electrode/ton of steel, 6 to 7 lbs has been achieved with moderately fast heats, 100 minutes.

3. A DC furnace, high speed heats may still have half the electrode consumption but the saving may be about 2.1/2 to 3 lbs. instead of the 5 or 6 lbs now considered as the saving.

4. The separation of most refining and metallurgical functions from the EAF will futher shorten heat times, thus saving carbon electrodes. Some of the flat bath superheating for casting is now possible under foamy slags or in a ladle heater, thus speeding the heat times.

5. The use of water-cooled non-consumable (NCE) electrodes can be installed for approximately $250,000 Canadian, for a one-furnace shop dropping to $180,000/fce for a 2-fce shop, possibly a little lower/fce for bigger shops.

6. The use of NCE's require 2-3 mins/heat, average for electrode assembly exchange which is a factor in heat time; this is a little longer than the normal slipping of carbon electrodes. This is not important in shops where caster sequences set the pace.

7. The maintenance cost of NCE's can be estimated for a particular shop.

8. The price of carbon electrodes in Canada has been dropping, now at about $1.60/lb Edmonton. It had been expected that the cost would increase, thus NCE's are not being installed at a great rate. Lower carbon costs may also slow the pace of DC furnace acceptance.

9. Mr. Pugh has no driving urge to move to DC furnaces as yet. He feels like others at this time, that the bottom problems are still of concern but would be open-minded to any demonstrated data that eliminates this problem.

10. At present, should his plant require increased power, and, flicker became a real problem, then this may be the key motive for the consideration of DC.

Ontario Hydro

Memorandum To DR. C.J. SIMPSON
Senior Research Engineer
Divisional Projects Dept

Location or Dept KR295

Date October 22, 1987

File 808.274(T)

Subject **Report on the Advanced Melting Technologies Symposium, Myrtle Beach, SC, October 4-6. 1987**

This symposium was limited to only 200 participants, but due to the specific nature of the agenda, the attendance consisted of an excellent cross section of the international leaders in each technology. The symposium was divided into four sessions:

- Existing and Modified EAF's
- DC Arc Furnaces
- Plasma and Induction Furnaces
- Coal-Based Processes.

Existing and Modified EAF's

The papers in this section outlined current and future alterations to increase capacity and efficiency of present EAF's. EAF's have trended toward operating at higher voltage which has influenced the industry in many ways. Higher voltages mean the ability to increase the size and/or throughput of furnaces, reduce the tap-to-tap times from 180 to 70 minutes, and cut the average electrode consumption from 6.5 to 2.6 kg/MT. The need for ladle furnaces and continuous casting for survival was emphasized. Operators must work towards the synchronization of the EAF and the con-caster using the ladle furnace for a buffer to carry out secondary metallurgy refining, and decrease the tap temperature (required superheat is provided by the ladle furnace) allowing one to shorten the tap time. The EAF must be used only as a melting unit.

The topic which was emphasized in this session was the use of scrap preheaters. The objective of scrap preheaters are to allow faster melting and for energy conservation ($\sim$50 kWh/MT). Many of the conventional scrap preheating concepts were presented with an explanation as to why they were not adopted. The more advanced concepts being considered today were also outlined and their capability of overcoming the traditional problems: process control, fumes in the buildings, warpage in the basket, and system complexity.

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The last topic was the "CONSTEEL" process and the operating results to date at Nucor Corporation. This process is a continuous steel making concept which employs scrap prehating, continuous feeding, dc arc furnace, and foamy slag operation. Some of the benefits inherent with the dc arc furnace are less noise, fume and dust. The foamy slag ensures tht 80% of the energy from the tip of the electrode is transferred to the slag. With a flat slag surface only about 30-40% of the electrode energy is transferred to the slag. Foamy slag also results in much less refractory wear at the slag line since there is much less direct radiation on the side walls.

The CONSTEEL concept has proven the technical feasibility of continuous feeding and tapping of EAF's. There is a feed chute on the side of the furnace which is supplied with preheated scrap from a feed conveyor. There have been no problems with the continuous feeding causing electrode breaking. The furnace is operated under a slight negative pressure and requires great operator training. The operators must know as much about the slag chemistry as the molten steel. There are some limitations as to the feed materials, ie bundles are not used due to their poor suitability for preheating.

The furnace is currently operated at 1565-1595°C at 40-50 minutes tap-to-tap time and 420 kWh/ton of liquid metal. The scrap is presently only preheated to 350°C because the conveyor loading procedure has not been optimized to provide a constant covering of feed on the conveyor. As a result, the oxy-fuel burners cannot be used in the preheating conveyor and preheating relies entirely on furnace off-gas. The immediate goal for preheating is to achieve about 500°C. The present furnace campagin is about two weeks at which time some repair work is done on the slag line. A 3-4 MT liquid heel is always maintained in the furnace. Nucor is quite happy with the current progress in optimizing the continuous operation but emphasized the importance of an intense training program prior to the transition.

DC Arc Furnaces

The papers in this session described several existing dc arc furnace facilities and their operating experience to-date. The operating experience presented included the level at which the anticipated advantages of dc furnaces had been realized.

The first paper was ASEA's dc retrofit to one of the Florida Steel's EAF's. This retrofit utilized the existing transformer and installed a water-cooled rectifier. A de-ionizer was also installed in order to keep the cooling water conductivity low. Two of the three electrode arms were removed and the remaining one was lengthened to reach the centre of the furnace. The ASEA dc furnace concept includes a single

top electrode with the other electrode on the bottom of the furnace. The bottom of the furnace consists of a copper plate which is connected to the electric busbars and a conducting magnesite-graphite refractory sits on the copper plate which makes the electrical contact with the molten steel. The conducting refractory consists of two layers: a 20% carbon working lining, and a 10% carbon insulating lining. The average service life of the working lining has been four weeks. With recent refractory improvements Florida Steel has increased the working life to fourteen weeks. At present the bottom refractory is inspected twice a day and 20 minutes of localized repairs are done every ten heats. The cold repairs are done on weekends and have averaged 0.9 kg of refractory/billet ton of steel. Due to the need for regular inspection only a 1-2 MT liquid heel is maintained, which results in the need for the first charge bucket of scrap to be one-third shredded scrap. Due to the solid non-conducting slag layer left after a weekend shut-down, the furnace must be charged with 6.8 MT of shredded scrap and oxy-fuel burners are used to establish a molten heel. It was reported that the required maintenance for the dc furnace was less in the area of electrical phase control but higher for the insulation between the roof and the shell.

At Florida Steel there are two EAF's, one ac and one dc. A comparison of the energy, electrode and refractory consumption is as follows:

	14 MW ac	11 MW dc
Energy Consumption (kWh/MT)	466	458
Electrode Consumption (kg/MT)	5	1.8
Refractory Consumption	Same (higher on side walls)	Same (higher on bottom)

Other advantages listed were the beneficial stirring pattern in the dc arc and greater control over fumes due to a fewer number of electrode port holes. Areas listed as requiring further development were the need for inter-changeable shells to avoid down times and the limited available bottom area restricting the scaling-up potential.

The dc furnace is operated at a 0.825 power factor for meltdown and 0.74 for refining stages. An air bellows is used for cooling below the furnace. The bottom plate is maintained between 150-205°C.

Florida Steel had a lot of trouble in the first few months. The main problems were with the bottom refractory, although tremendous progress has been made, the problems are not yet considered solved. The bottom lining has been improved to survive as long as 751 heats with some local repairs but the average life in the first year has only been 200 heats.

The worst wear occurred on the bottom directly below the top electrode (two diameter area). There was initially a problem with the refractory at the point where the side wall meets the bottom ("knuckle"). To remedy the situation, the five rows of brick on the outer diameter of the bottom were changed from conducting to non-conducting refractory (stronger). Initially, the dc furnace had 8% of unexpected downtime due to refractories. This figure has been cut to 1% for the last six months. The electrode size was also changed from 40.6 to 45.7 cm diameter in order to lower the butt losses during refining. This resulted in a drop in electode consumption from 2.25 to 1.81 kg.

Florida Steel also announced plans to construct a new 60 MT meltshop at Tampa. The deal has not yet been signed but the furnace will most likely be dc.

The second paper was presented by CLECIM from France. Clecim presented very strong arguments in favour of a multi-top electrode dc arc furnace. Clecim has licensed this technology from the French Iron & Steel Research Institute (IRSID). Clecim strongly believes the upper limit for a single electrode dc furnace is 50 MT due to the limited cross sectional area for current density. Clecim presented a comparison for a 60 MW furnace with a power density of 800 kW/MT. The single electrode furnace at 500 V would require 120 kA where a three electrode furnace would only require 40 kA/electrode. The calculations for electrode consumption revealed a lower value for the multi-electrode dc arc than for the larger single electrode. However, ASEA and Clecim had strongly opposing opinions as to the upper limit of the single electrode dc furnace.

Clecim's multi electrode dc furnace has three bottom electrodes each paired with one 50.8 cm top electrode. The furnace holds 85 MT of hot metal with 75 MT of tapping capacity, producing 1000 MT/day. The energy consumption is about 480 kWh/MT with no oxy-fuel, scrap preheating or ladles; the goal is 420 kWh/MT. The electrode consumption is presently about 2 kg/MT with a goal of 1.8 kg/MT. The furnace has been operating since January, 1986.

The final paper outlined the GHH/Brown Boveri Corp dc arc furnace at Nucor Steel and the operating experience to date. The BBC furnace uses contact pins through the refractory for the bottom electrode. The furnace produces 14 MT/hr and the electrode consumption dropped from 4.1 kg/MT for the ac furnace to 1.8 kg/MT for the dc furnace. The furnace requires three buckets of charge/heat and has a 30 MT tapping capacity. From January 1985 to August 1987 the furnace has produced 186,000 billet MT with an average tap-to-tap time of 129 minutes. The bottom electrode contact was replaced about every 10,000 MT.

Nucor has the advantage of having two identical furnaces side-by-side, only one is ac and the other is dc. It is therefore very convenient to compare operating data; this comparison was carried out for 38 consecutive heats where all inputs and outputs were weighed or measured.

This comparison revealed that 3.3% less electrical energy was required with the dc furnace (463 kWh/MT vs 479 kWh/MT) and substantially lower quantities of oxygen (400 scf with dc and 650 scf in the ac charge). The output of both furnaces were virtually the same.

The dc furnace operates with a liquid heel and a foamy slag. The charge is melted like a donut from the centre outwards in the dc furnace with the arc being shielded. In the ac furnace the arc is pushed by an electro-magnetic force towards the outside of the furnace causing hot spots on the refractory. The dc furnace also has the load applied more uniformly over the cross-section of the electrode. The dust losses with both furnaces were nearly equal, 18 kg/MT.

Plasma and Induction Furnaces

The papers in this session covered some operating results from some existing plasma and induction installations as well as some potential applications of plasma technologies.

The first paper reported on the progress made with Krupp's ac plasma furnace. Krupp operates their furnace in the transferred mode with a hot electrode and ac power. In this configuration the current passes from one torch through the melt and back to a second torch. Krupp claims this to be the lowest cost plasma torch configuration to operate. The only requirement is that one needs a power supply with a steep-pass through the zero current. There were initially reports of increased nitrogen pick-up from the plasma arc. Krupp stated that this is not a problem in large furnaces. Although the plasma acts as a nitrogen injection pump, with large molten surface areas equilibrium will occur with the atmosphere.

Krupp's plans for this furnace concept are in the area of scrap melting, ladle heating and tundish heating. The torches that are presently used are 112 mm x 3 m and operate up to 3.6 MW with an electrode life of 100 hr. They have operated a 20 MVA, 10-15 MT furnace since late 1986. The cost of the Ar and N_2 required are roughly equivalent to 1.5 kg/MT of electrode.

Krupp presently is constructing an ac plasma tundish heater and also have plans to install this ac plasma heating concept in a ladle during Christmas, 1987. Krupp suggested the greatest potential for their non-transferred ac plasma is in ladle and tundish applications.

The second paper was on advances made in the Plasmascrap process from SKF Steel, Sweden. This plasma furnace is designed as an economical melting unit. It has the limitation of no superheating or refining capability and the scrap cannot be too small or large. The melting rate of the unit is 3 MT/hr. Coal is combusted in the plasma gas to provide additional low cost heat. The off-gas leaving the furnace is presently at about 400-500°C. There is some problem with channelling of gases which results in a relatively high temperature off-gas and 25% higher than theoretical consumption of electrical energy.

The proposed applications for such a unit are:

- combined with an EAF to increase capacity and decrease melting costs;
- increase the scrap rate in BOF's;
- decrease the melting cost in cupola's.

The last paper on plasma scrap furnaces was from Plasma Energy Corp. PEC has no production facilities but have operated a relatively large pilot facility, 3.5 MW. The furnace has melted about 100 MT of scrap thus far more as a demonstration of the principle than process development. PEC has a torch which is designed to operate at 12 MW and has been tested to 6 MW.

Ajax Magnethermic presented a paper on induction melting of scrap in large metal mixers. It was emphasized again that this unit is to produce iron, not steel. The capacity of the mixer in S. Africa is 1800 MT and is equipped with six 2500 kW channel inductors. It is used for superheating and primary melting (34 MT/hr) to eliminate interruptions to their casting operations. The limitation is the amount of room on the side of the mixer to mount the inductors. These large inductors can pump 700-1000 MT/hr of hot metal through the channel. The vessel is lined with high alumina refractory and it was stressed the importance of the refractory life due to the size of the vessel. The refractory life is approximately six months. The vessel must operate with a substantial molten heel making intermittent refractory repair impossible.

Coal-Based Processes

The most interesting paper in this session was the report on the operation of the Energy Optimizing Furnace (EOF) by Korf Lurgi Stahl Engineering. The installation was retrofitted to an existing 30 MT open hearth furnace in Brazil. The EOF produces 24 MT/hr of hot metal. Since the retrofit the furnace production has increased from 180,000 to 360,000 MT/year. This furnace is a shaft-type design where the melting takes place on the bottom and there are three stages of scrap preheating with each stage supported by a set of hydraulically operated fingers.

DR. C.J. SIMPSON

October 22, 1987

The furnace was designed to melt 100% scrap but has only achieved up to 80% scrap so far. No scrap preparation is required but turnings and pieces longer than five feet cannot be used because of the support fingers holding each of the three preheated scrap levels.

The furnace is a split furnace shell with water-cooling above the slag-line and interchangeable bottom shells to avoid long delays for refractory re-lining. The furnace and preheating shaft both operate under a negative pressure.

This furnace and its operating data received tremendous interest from all participants. The reduction in refractory, labour and energy appeared very appealing, especially since Korf Lurgi Engineering are marketing and guaranteeing the technology.

CONCLUSIONS

Generally, the conference provided detailed information on many novel electric furnace concepts and actual operating benefits and problems which have been encountered during production. In most cases this very recent (August/87) operating data given by users of the technology as opposed to suppliers, gave a very realistic view of what one may expect in commercial operation. The operating data gained from the modified EAF session and the dc arc session will be especially useful for our study in assessing the potential for dc arc furnaces in Ontario. The symposium gave an excellent summary of what can be done to optimize the operation of existing ac EAF's as well as the problems and benefits which have been realized during the operation of dc arc furnaces. The information and contacts obtained at the symposium will be invaluable for carrying out the study on dc arc furnaces.

R. Reesor

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/dr

cc Dr. J. Brown
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Memorandum To DR. C.J. SIMPSON
Senior Research Engineer
Divisional Projects Dept

Date November 17, 1987

Location or Dept KR295

File 808.274(T)

Subject **Visit to INCO DC Arc Furnace Pilot Plant**

Date of Visit: November 5, 1987
Personnel Involved:
Richard Stratton-Crawley, INCO
Richard (Dick) Wilkwerth, INCO

C.J. Simpson, OHRD
R. Reesor, OHRD

SUMMARY

Although a great deal of progress has been made in the development of DC arc furnaces, the design of the hearth is still the weakest link. Different types of operations require different types of bottom electrodes or hearths.

The proposed OH pilot plant will lend itself to furnace hearth/bottom electrode development for DC furnace applications.

The INCO DC arc furnace pilot plant was visited by the above. The guide was Richard Wilkerth from the INCO Research Station. The furnace was not operating since an explosion, which occurred during start-up, had damaged the furnace roof. Subsequently, the pilot plant furnace and INCO's interest in DC arc technology was discussed with Stratton-Crawley at the INCO Roy Gordon Research Centre.

INCO's main incentive to investing in DC arc furnace technology is to increase smelting intensity. It was stated that the maximum power density for an AC arc furnace is 100 kW/m^2 whereas a DC furnace can be operated at 700 kW/m^2. Also, the reduced noise level experienced with DC as compared to AC operation was quoted as an example for moving towards DC smelting technology. The power densities quoted

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are for sulphide or ferro-nickel technology. Steel furnaces are operating at much higher power densities. For example, the LASCO C furnace is operating at a power density of 3290 kW/m^2. Falconbridge ferro-nickel smelting furnaces have been operated at power densities of up to 500 kW/m^2.

Pilot Plant Description

The pilot plant is located at INCO's pilot plant facilities in Port Colborne. Three phase 34.5 kV power is transformed to 149 volts and then rectified by a thyristor-controlled rectifier supplied by Thyristor Devices Inc. The cable leading from the transformer to the rectifier has been sized wrongly, which results in a voltage drop of 35 volts when operating at full power of 1.2 MW.

Overheating of the rectifier was experienced during the start-up of the furnace as a result of AC coupling with the rectifier support frame and the metal doors. The problem was overcome by replacing the mild steel support by stainless steel and the doors by a non-conducting material.

The furnace has an ID of 7 ft (213 cm). It is equipped with a 9" diameter (22.86 cm) hollow graphite top electrode and a bottom electrode.

The electrode hoist was supplied by Whiting. The motor drive was undersized, which made automatic electrode operation impossible. Thus design error can be readily modified. A 1.1/2" diameter hole has been drilled centrally through the electrodes to permit feeding of solids and gas through the electrodes.

The bottom hearth was initially constructed of conducting carbon magnesite bricks. This design was abandoned because of carbon pick-up experienced by utility nickel smelted in the furnace and the rapid hearth erosion caused by the carbon take-up by the metal. The present hearth consists of a copper plate overlaid by carbon magnesite bricks, which are topped off by steel cased magnesite bricks. This hearth construction is similar to that employed by Middleburg in South Africa. The hearth is 27" thick, grounded and electrically insulated from the furnace shell.

The feeding system consists of two belt feeders, one for coke fines and the other for nickel oxide. A conveyor belt transports the feed mix to a feed hopper which is connected to the central electrode hole. The feed pipe is electrically insulated from the electrode. Gas injection into the feed stream of solids minimizes the chances of feed hang-up in the feed system.

The exhaust gases from the furnace are burned in an after burner and then passed into a gas quencher. The furnace is equipped with metal and slag tap holes located approximately 10" above each other.

Instrumentation for the electric furnace panel was supplied by Thyristor Devices. The meters are of a poor quality and will be replaced to improve the accuracy of the read-out.

Furnace Start-Up

The furnace is started by loading approximately 1000 lbs of carbonyl pellets topped with carbon fines into the furnace and then striking the arc. It is claimed that the furnace can be started readily by using this procedure.

Future Applications for DC Arc Furnaces

It was stated that INCO has a backlog of programs of at least two years for their furnace. No specifics were volunteered, except that the replacement of the TBRC's at Copper Cliff is being considered and that smelting of PM materials is an attractive proposition.

INCO is not considering to convert their Thompson matte smelting furnaces from AC to DC. This conversion is costly and does not have an apparent advantage over the current smelting system.

Hearth Design

Various types of hearth designs used by different companies were discussed:

ASEA	Conductive carbon-magnesite Brick
GHH/BBV	Pin type
IRSID	Water cooled ingot.

As mentioned above, INCO's started up with the ASEA type hearth design. They soon found that this hearth was corroded by the action of nickel when reducing nickel oxide. Nickel dissolved carbon.

They rejected the pin type hearth since the pins will be attacked by sulphides. However, they are using steel clad refractories. This is really the same as pins.

The above type of hearths will most likely have a short life when smelting sulphides.

DR. C.J. SIMPSON November 17, 1987

INCO rejects the IRSID water-cooled hearth since they consider that there is an inherent danger in this design because of the possibility of water leaking into the system.

This type of hearth will have to be used for sulphide smelting. It is believed that a safe design can be worked out and that INCO is overly concerned.

The OH pilot plant will afford an excellent opportunity to test out different types of hearth designs for bottom electrode arc furnaces.

Florida Steel has recently changed their hearth design which is of the ASEA type. The main areas attacked were at the hearth's periphery and under the electrode. The new hearth is of a "doughnut" type design. A non-conducting area is placed under the electrode and another around the periphery of the hearth.

R. Reesor

R.A. Bergman for
Consultant
Materials Processing
(Ext 405+70059)

/dr

cc Mr. R. Reesor

January 7, 1988

TRIP REPORT

Company:	Florida Steel Corporation
Location:	Tampa, Florida
Date:	December 18, 1987
Present:	David Reese, ASEA, Project Manager
	Kevin Duda, Florida Steel, Melt Shop Supervisor
	R. Reesor, OHRD
	H. Whitmell, OHRD
	R.A. Bergman, OHRD

Purpose: To obtain upto-date information on the DC furnace operation of Florida Steel through discussions with operators and the supplier, and observe the furnace operation.

SUMMARY

Florida Steel operates two similar furnaces. One furnace is operated on DC and the other on AC. The DC furnace is said to have a cost advantage of $8.00/ton of steel over the AC furnace. The main reason for the difference in cost is found in the electrode consumption which averages 11 lbs/ton for the AC operation and has now reached a low of 3.2 lbs/ton of hot metal for the DC furnace. Minor savings can be also found in refractory and energy consumption. The quoted figure for the AC electrode consumption is probably high, since at an electrode cost of $1.21/lb, a saving of $9.44 can be calculated. The difference in electrode cost between AC and DC will most likely decrease in the future for two reasons:

1. the electrode cost is expected to drop to $0.80/lb.

2. Water cooling of the electrodes has been instituted by Florida Steel on both furnaces.

The visit has helped to clarify a number of issues which were not clear from the literature study.

1. General: Florida Steel, Tampa Works, has two electric arc furnaces:

	DC	AC
Supplier	Whiting	Electromelt
Year	1966	1974
Nominal capacity items	33	33.5
Diameter, ft	12.5	13.5
Transformer, MVA	18	18
Melt-down power, MW	11	14
Refining power, MW	9	11
Electrode diameter, in.	18	16
Charges per heat	3	2

The DC furnace was started in March of 1985. The operation of the furnace has been found to be satisfactory. No serious operating problems have been experienced. The single electrode break since start-up was not related to the DC operation.

ASEA and Florida Steel have an arrangement through which both companies share in the operating savings.

Florida Steel is planning to increase the plant capacity by adding a 60-ton furnace. Discussions are underway during which it will be decided whether the new furnace will be an AC or DC furnace. At the present time it appears very likely that it will be DC.

2. Electrode Consumption: Over the past few months the electrode consumption on the DC furnace has been reduced from 4 to 3.2 lbs/ton of metal. This is most likely due to the recent addition of a water cooling spray to the electrode. An electrode consumption of 11 lbs is quoted for the AC furnace; this is probably high since this would amount to a saving of $9.44/ton of steel at an electrode cost of $1.21/lb. The total cost saving realized by going to DC was quoted at $8.00/ton of metal. This includes also minor savings in refractory and power.

Cooling of the electrodes by water sprays has been introduced recently on both the AC and DC furnace. The data available as yet is very preliminary on how much this will reduce the electrode consumption. The estimate is 2 to 3 lbs/ton of metal for an AC furnace. Some problems have been experienced with clogging of the water holes from dust build-up on the outside.

The reduction in electrode consumption achieved by direct water cooling will decrease the financial incentive of the DC furnace operation.

3. Furnace Hearth: A furnace hearth life of up to 760 heats has been achieved. The norm is 300 to 400 heats. The hearth is constructed as follows:

Safety lining Magnesite-Graphite, 10% carbon, 9"
Intermediate lining Magnesite-Graphite, 20% carbon, 11"
Working lining Magnesite-Graphite, 20% carbon, 18".

The current is introduced by means of an air-cooled copper plate on which the safety lining rests.

Side wall repairs by gunning and bottom patching are carried out on the run. Major repairs are done on weekends. The furnace is allowed to cool on Saturdays, and the cleaning out and repairs are performed on Sunday by the furnace operators. Florida Steel does not have a refractory department. Badly corroded bricks are removed to obtain a flat surface. The hearth is then built up with 3" bricks. The number of courses required depends on the depth of hearth attack. The wear is much greater in the centre of the hearth and as a result part way through the furnace campaign the centre refractories are replaced with stronger non-conducting bricks. The complete working lining is replaced every 5 to 14 weeks, depending on the condition of the furnace bottom. Furnace bottom life has increased significantly since sintered magnesia bricks were replaced by fused high purity magnesia bricks. Harbison Walker and Didier are the main suppliers of refractory. Both have cooperated closely with Florida Steel in the development of hearth bricks, espeically designed for conducting hearths.

4. Energy Consumption: The energy consumption in the DC furnace is slightly below that of the AC furnace, 458 as compared to 466 kWh/ton. Door burners and lances are only used during start-up with a new furnace bottom.

5. Environmental: Very little difference between the noise level of the AC and DC furnace was observed.

6. Furnace Control: During the visit the furnace was operating at 40,000 A and 360 volts or 14.4 MW. The power input to the furnace is controlled manually, unlike the Nucor furnace which uses computer programming. It also appears that the control on this furnace is different from that of the Nucor furnace. Volts and current fluctuated in the Florida Steel furnace, where the current was kept constant at Nucor.

7. Insulaton: The electrical insulation between the furnace shell and bottom has been changed from the original design. The flange connection has been changed in order to leave a space between them to accommodate quick removal of dust build-up. In the initial design there was no space and dust would build up causing shorting. The maintenance cost and downtime involved resulted in a new design whereby the dust can be removed routinely with compressed air without any furnace interruption.

8. Electrical Supply: The electrical power supply conversion was relatively trouble-free. The only problems worth noting were with faulty vacuum switches and fuses. This has been corrected and the system is running quite smoothly.

R. Reeson

for R.A. Bergman
Consultant
Materials Processing
Research Division

/dr

January 8, 1988

TRIP TO NUCOR STEEL, DARLINGTON, SOUTH CAROLINA

Date of Visit:	December 17, 1987	
Present:	Patrick B. Spivey	Nucor Steel
	R. Reesor	OHRD
	H. Whitmell	OHRD
	R. Bergman	OHRD
Purpose:	To observe the steel melting operation at Nucor Steel and discuss it with operating staff to obtain up-to-date information and thoughts from the user of a DC arc furnace.	

SUMMARY

Nucor appears to be satisfied with the operation of their DC arc furnace. Start-up of the unit has been easier than expected. Performance has been reliable and the carbon consumption has been decreased from 10.5 lbs/ton of hot metal to 3.5.

The noise emission from the furnace was higher than expected from the literature reports and quite comparable to that of the AC furnace operating next to it.

When asked whether Nucor is planning to convert another furnace to DC or if they are planning to purchase a DC rather than an AC furnace in their scheduled expansion, the answer did not indicate that Nucor was committed to DC. They will evaluate the situation. Their planned expansion will require a 100-120 ton EAF and Nucor does not feel comfortable in jumping from their 30 ton DC to a 120 ton DC. The expansion will most likely include an AC furnace.

It was a useful visit insofar as it permitted us to obtain clarification on some points that had been raised in the past and that it gave us the opportunity to observe a DC furnace in operation.

GENERAL

The OH group was welcomed by P. Spivey who showed a video of the furnace design principles and operation. This was followed by a detailed discussion during which a number of our questions were answered, but not all, and finally a visit to the melt shop where the DC and AC furnace were observed in operation.

The information gathered to date from the literature on the Nucor operation is essentially correct. It was possible to fill in a number of gaps which are discussed below.

1. Nucor operates three 30 ton 12 MVA electric arc furnaces in #1 melt shop. Two of these furnaces are operated as three phase AC furnaces, whereas the third furnace has been converted to DC. The electrode diameter for the AC furnaces is 14 in., whereas a 16 in. electrode powers the DC furnace. No.2 melt shop has a 50 and 75 ton furnace respectively, powered by 27 MVA transformers. Nucor is planning to add a new 100 ton furnace and use one of the existing furnaces as a ladle furnace.

The product line consists of wire, angles and billets.

The general impression was that Nucor is a well-run, very aggressive electric furnace shop; not afraid to try new technologies on a commercial scale.

2. Electrode Consumption: The electrode consumption in the DC furnaces has averaged 3.5 lbs/ton over the past few months, as compared to 10.5 lbs for the AC furnaces. Large 100 ton arc furnaces are achieving electrode consumptions below 7 lbs/ton if used only as melters. It is believed that the saving in electrode consumption for these furnaces is much less than that for the small, low-powered furnaces.

No electrode breaks have been experienced since conversion to DC.

3. Refractory Consumption: The sidewall refractory consumption is less for the DC than for the AC furnace. No consumption figures could be obtained. The lower section of the furnace is repaired by gunning; the furnace hearth has a life of about 10,000 tons. It was stated that the total refractory cost has been lowered from $2.00 to less than $1.50 per ton.

4. Furnace Hearth: The furnace hearth is the most critical link in a DC furnace. As stated above, Nucor is achieving a hearth life of 10,000 tons.

The furnace is operated with a hot heel and foamy slag practice. The metal heel protects the furnace bottom to a large extent. Furnace bottom life has also been lengthened to about 330 heats by optimizing the size and arrangement of the eighty contact pins. We were not able to obtain the size of the contact pins. There are no longer contact pins located directly below the graphite electrode. They are arranged in a pinwheel pattern surrounding the non-conductive centre of the hearth in a two to three feet wide band. Each contact pin is equipped with a thermocouple to indicate to the operator the status of the pins. Temperatures of up to 530°F (288°C) were recorded. If temperatures increase unduly unexpectedly, the operator can increase the cooling and/or lower the furnace operating current.

Hearth repairs are no longer carried out. Rather the hearth is replaced when it has come to the end of its useful life. The damaged hearth is pressed out by four hydraulic presses and then picked up by the crane and removed. A new hearth is lowered into position. A two to three inch gap is left between the new hearth and the furnace lining, which is filled by a combination of ramming mix and castable. The hearth replacement requires approximately eight hours. Nucor hopes to make substantial efforts to shorten this time. No metal leaks have been experienced.

5. Furnace Productivity: The furnace productivity was confirmed as 13.5 tons/hr or 37.5 lbs/min/MW and the tap to tap time is 129 minutes. No breakdown was obtained for the various unit operatons which make up the tap to tap time. It was claimed that this information is not available.

6. Specific Energy Consumption: Nucor uses neither oxy-fuel burners nor employs charge preheating on their 30 ton furnaces. A recent trial has shown that the specific energy cost for the DC furnace is 3.3% lower than for the AC furnace inspite of the fact that the AC furnace has oxygen at a rate of 500 SCFM for 40 minutes as compared to 24 minutes in the DC furnace.

7. Furnace Reliability: Nucor has found the DC furnace to be as reliable in operating performance as the AC furnace.

8. Product Quality: Both types of furnaces produce the same type of steel and low alloy steel. Absolutely no difference in product quality has been observed.

9. Electrical Flicker: The furnaces are equipped with static VAR Systems. Electrical flicker is of no concern to Nucor, since they have a direct feeder line to the nuclear power station located about 17 miles from the plant.

10. Working Conditions: Little difference in noise level between the DC and AC operation was observed. Also fume emission appeared to be equivalent.

11. Capital Cost: Spivey did not answer our question with regard to relative capital cost of DC and AC furnaces. He referred us to E. Mueller of Brown Boveri Corporation, he estimates that the saving in electrode cost will pay for the conversion cost from AC to DC in the Nucor plant in 1 to 3 years and the overall cost savings is about $5/ton of hot metal. He wasn't really specific, but he did state that there was not much difference in capital cost to build an AC or a DC furnace operation.

When converting a plant from AC to DC or building a new DC arc furnace, electrode consumption is only one part of the argument to justify the capital expense. Each conversion has to be justified based on specific local conditions. There is no hard and fast rule to form a basis from which it can be decided to either go AC or DC.

12. Maximum DC Furnace Size: This could be limited by the maximum electrode size available (28"). Nobody is sure how big a single electrode DC furnace can be built. Before one thinks of a 100 ton furnace someone has to convert or build a 60 ton single electric arc furnace.

13. Control Strategy: The furnace has been computer programmed; the power is brought as quickly as possible up to the maximum rate in steps. This rate depends on the type of scrap charged. The current is the independent variable, where the voltage and hence power is controlled.

R. Reeson

for R. Bergman
Consultant
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/dr

NUCOR STEEL DC ARC FURNACE (DECEMBER 1987)

176685-RD

Memorandum To DR.C.J.SIMPSON
Principal Research Engineer
Divisional Operations Dept

Location or Dept KR295

Date January 29, 1988

File 808.274(T)

Subject **Visit to J. Mulcahy Enterprises Inc (JME), Whitby, Ontario**

J. Duckworth	JME
R. McKellar	Industrial Marketing
J. Welch	Industrial Marketing
H. Whitmell	OHRD
R. Reesor	OHRD

On January 21, 1988 a discussion was held with Mr. Jim Duckworth of JME on DC arc furnaces. JME is the North American representative of Clecim, France. Clecim has licensed IRSID's (France's Iron & Steel Research Institute) patent for the bottom electrode of a DC furnace. Clecim's DC furnace concept employs three graphite top electrodes and three water-cooled steel insert bottom electrodes. The rationale for using three sets of electrodes is to avoid the scale-up problems associated with the high current densitites on single electrodes.

Many North American steel producers are skeptical about the safety of using water cooling below the furnace. Clecim maintains they are confident that the furnace is safe. The furnace they have in operation at the Societe Metallurgique de l'Escaut (SME) in France has run for eighteen months without any accidents.

Mr. Duckworth gave a slide presentation of Clecim's DC arc furnace design and some recent operating data on the SME installation. The following is a comparison of operating data from November 1986 to November 1987:

November 1986	November 1987
12 heats/day	14-15 heats/day
990 billet ton/day	1100 billet ton/day
4.4 lb of electrode/ton	4.0 lb of electrode/ton
454 kWh/ton	454 kWh/ton
565 scf of oxygen/ton	565 scf of oxygen/ton
p.f. = 0.75 boredown)	Same
0.85 melting)	Same
500 mm electrode	500 mm electrode
48 MW (3 electrodes x 16 MW)	Upto 60 MW (3 electrodes x 20 MW)
82.5 ton/Heat; 14 ton/Heel	94.6 ton/Heat
68 ton/Tap	81.4 ton/Tap

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DR. C.J. SIMPSON January 29, 1988

The pitch diameter of the top graphite electrode is larger than the pitch diameter of the water-cooled bottom electrodes. This caused the arcs to focus toward the centre of the furnace as well as effectively melting the scrap from the outside walls of the furnace.

There is a central hole between the graphite electrodes which is used for alloy (refining) additions. SME does not use a ladle furnace and therefore must superheat the melt to a certain degree (1705°C) for refining. The furnace productivity is also limited by insufficient caster capacity. This results in longer tap-to-tap times and higher electrode consumption than would be possible if the furnace was used only as a melter.

JME have carried out some economic evaluations. Although it was emphasized these calculations are quite site-specific, the calculated savings of the DC furnace over an existing AC furnace is about $8-$10/ton.

Mr. Duckworth was quite optimistic that there would be some announcements in 1988 regarding new applications of the Clecim furnace resulting from ongoing proposals.

R. Reesor

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Engineer
Process Metallurgy
(Ext 7193)

/dr

cc Attendees
R. Bergman